EVALUATION OF FIRE DAMAGE OF CONCRETE SLABS

By

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Finally, I wish to dedicate this dissertation to my family, especially my wife, Kuang-jen Huang. Without her support and dedication, this work might never have been completed.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Abstract of Dissertation Presented to the Graduate School of the University of Florida in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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There are two major building structure damages caused by fire: the reduction of fire resistance and the reduction of strength. Both are important factors in determining the reusability of a structure after it has been exposed to fire. An experimentally validated analytical technique for evaluating the residual fire endurance of structural elements after fire is currently unavailable. Although nondestructive test methods have been used for evaluating the residual strength of concrete structural members, no systematic analysis has ever been done.

The purpose of this dissertation is to conduct a comprehensive pilot study of residual fire endurance and strength of concrete slabs after exposure to fire. A small-scale fire test, two nondestructive tests, and a destructive test were conducted to evaluate the effects of three factors,

i.e., exposure severity, re-curing condition, and re-curing time lapse, on the residual fire endurance, Schmidt hammer rebound number, pulse velocity, and compressive strength of concrete slabs made of typical Florida porous limestone and Type I Portland cement. A statistical model was established to investigate the effects of test factors on the results and the correlation between nondestructive and destructive test results. It was found that when concrete slabs are exposed to fire more than thirty minutes, the environmental factors do not affect the test results significantly, but the reduction of fire endurance is obvious. Therefore, the consideration of fire endurance is critical for fire damage evaluation and should not be overlooked. A preliminary investigation on using nondestructive test methods to evaluate both the residual fire endurance and strength of concrete slabs after exposure to fire is presented, and further studies to validate these methods are evidently needed. A reference is established for applications and further research.

CHAPTER 1
INTRODUCTION

1.1 Statement of the Problem

All new buildings erected in the United States are subject to regulatory control for health and safety purposes. In modern building design, fire safety is always an important consideration. For fire safety, building codes and fire codes regulate the specifications for the fire resistance of buildings, contents, and linings; the system for suppression, detection, alarm, and smoke control; firefighting equipment; and egress provisions. It is generally agreed that the most effective method of preventing the spread of fire in a large building is to divide the building into a number of compartments by appropriately using elements of satisfactory fire endurance (Blanchard & Harmathy 1964). It is necessary, consequently, for the designer to understand how the fire endurance requirements are arrived at and to which elements they apply.

Fire endurance is a term specifying the time that a building element is capable of functioning as a fire barrier in a building fire. It is a characteristic property of a construction, and as such can be determined by means of suitably devised fire tests. In the United States, the

American Society for Testing and Materials (ASTM) E-119 Standard, "Test Methods for Fire Tests of Building Construction and Materials," is the accepted verification method to test the fire resistance rating of a structural assembly or element. This standard fire test is carried out by exposing a surface of a test specimen to heat in a furnace so as to simulate its exposure to heat in a fire. The test specimen is, generally, representative of the construction elements or materials. This fire test standard specifies the method of evaluating the time period at which the specimen fails, i.e., ceases to function as a fire barrier. This time period is defined as the fire endurance of the corresponding construction.

Fire is one of the most serious risks to any structure, and the increasing use of concrete as a construction material has led to an increased chance of its exposure to fire. As a result, it is necessary to develop a greater understanding of the influence of high temperature on the performance of concrete structural elements and construction assemblies. Architects, building owners, insurance companies, structural engineers, and code enforcement officials need a method to evaluate the extent of damage to a structure after a fire.

When evaluating the integrity of structures for further use after exposure to fire, two factors should be examined. The first factor is to determine whether the fire endurance of a specific structural element or structural assembly was

reduced to a value lower than that required by the building code. The second factor is to determine the residual strength of concrete. Both factors are important elements in determining the feasibility of repair of the structure. Reduced fire endurance and strength may result in a reduction in the ability of concrete to confine future fires and/or to support the building's design loads. Because of these potential reductions, it is necessary to develop a technique to investigate the residual fire endurance and residual strength of fire-exposed structural members and to determine whether the structural elements should be replaced, repaired, or kept in use.

ASTM E-119 is the only test standard accepted by current code authorities in the United States for evaluating the fire endurance of construction elements and materials. Therefore, for consistency, the residual fire endurance of burned construction elements should be evaluated by using the ASTM E-119 test standard. If reference data can be established for residual fire endurance by laboratory tests, and also, if nondestructive test techniques can be developed to evaluate the residual fire endurance and strength of concrete elements, it will be extremely helpful to the architects, building owners, insurance companies, structural engineers, and code enforcement officials for evaluating the fire-damaged building.

Evaluation of fire-damaged concrete has been done by using different tests which are valuable but limited (Kordina et al. 1986; Lie et al. 1986; Muenow & Abrams 1986; Tovey 1986; and Sansalone & Carino 1988). Several nondestructive test methods have been developed for locating defects in concrete and estimating concrete compressive strength (Muenow & Abrams 1986). However, a correlation between strength and test measurement based on standard tests conducted under controlled laboratory conditions has not been established.

1.2 Purpose

The purpose of this study is to investigate how external factors affect the residual fire endurance and properties of burned concrete. The problems studied included: (a) Can we determine the intensity and duration of a fire that has occurred in a structure?; (b) Can concrete strength be regained or grow continuously with time after fire?; and (c) How does the re-absorption of moisture in concrete affect the fire endurance and the material properties?

In order to develop a comprehensive understanding of residual fire endurance and residual compressive strength of concrete elements exposed to fire, this study focused on three tasks. One task was to evaluate the residual fire endurance of burned concrete slabs by using the ASTM E-119 Standard Fire Test Methods. The second task was to estimate the fire damage to the concrete by using two different nondestructive methods:

Schmidt rebound hammer and ultrasonic pulse velocity meter. The third task was to test the remaining compressive strength of core samples taken from each concrete slab. The entire study was designed to investigate the possible cause-and-effect relationships of three different variables (i.e., pre-exposure fire severity, re-curing method, and re-curing time lapse) by exposing specimens to eight (2 X 2 X 2 factorial design) different treatments and comparing the results to one untreated control group. The test results were expected to provide information on how the three factors affect the residual fire endurance, Schmidt hammer rebound numbers, ultrasonic pulse velocities, and the residual compressive strength of concrete. The relationships between the results of nondestructive tests and a destructive test also were examined. The possibility of using nondestructive test methods to evaluate residual fire endurance was investigated. Additionally, the temperature history within each specimen as well as the ambient temperature and moisture were recorded.

The importance of this research can be summarized as follows:

1. A systematic study of the residual fire endurance in burned concrete elements;
2. Uses a combination of statistical methods and standard fire test methods to investigate the fire endurance of burned concrete elements (the ASTM E-

119 standard fire test typically requires a single test);

3. A statistical study to compare nondestructive and destructive test methods by using the same experimental design used in residual fire endurance tests; and
4. Using nondestructive test methods to evaluate residual fire endurance of concrete slabs after fire.

1.3 Hypotheses

The hypotheses for this study can be summarized as follows:

1. Residual fire endurance and residual compressive strength of burned concrete elements will be reduced by severe fire exposure.
2. The relationships between test results of nondestructive and destructive tests can be established.

1.4 Technical Approach

The research methods used include three major parts:

1. A literature search to describe the development of standard fire tests, the relationship between the fire tests and building fire safety design, fire test techniques, nondestructive test techniques,

and the properties of concrete at elevated temperatures.

2. An experimental method that included:
   a. A fire endurance test to establish the initial and residual fire endurance of concrete slabs by following ASTM E-119 test procedures.
   b. Two nondestructive tests to evaluate the extent of damage to concrete elements after fire exposure.
   c. Tests on cored samples to evaluate compressive strength of concrete after fire exposure.

   The experimental data obtained by means of the test equipment were: (a) the temperature history of the unexposed surface of each specimen (°F-minute); (b) the temperature history within each specimen (°F-minute); (c) fire endurance including initial fire endurance and residual fire endurance of each specimen (minutes); (d) Schmidt hammer rebound numbers; (e) pulse velocities; and (f) compressive strength of cored concrete.
3. A statistical analysis of experimental data to test hypotheses and reach conclusions.

1.5 Limitations

The ASTM E-119 standard test method has been criticized by several fire scientists (Babrauskas & Williamson 1978;

Harmathy 1979; Brannigan 1982) for its weakness and deficiencies; but, the eighty-year-old methodology incorporated in most U.S. building codes has yet to be replaced. Thus, this standard test was employed in this study because it is the only standard method to evaluate the fire endurance of construction elements and materials.

The other reason for using ASTM E-119 standard fire test procedures is to simulate real fire conditions. However, due to the special characteristics of the standard time-temperature curve, e.g., the furnace temperature reaches 1000°F in 5 minutes, it is difficult to use it for a systematic study of concrete properties at high temperatures. In other words, the standard time-temperature curve is too severe for a fundamental scientific study. If the specimens were put in a furnace at a fixed temperature for a fixed time period and then retested by using ASTM E-119, more data and information on concrete behavior could be obtained. However, such a procedure would not have the consistency of standard test procedures and a real fire simulation. As a preliminary and pilot study, the ASTM E-119 time-temperature curve was used in this study to simulate the pre-exposure severity and the test fire exposure rather than to pre-expose the specimen to a fixed-temperature environment for a certain time period. This procedure is more helpful to the code authorities who adopted the standard fire test as the only verification method to identify the fire endurance of construction elements.

According to ASTM E-119 standard test procedures, the specimen can fail in three ways: (a) by collapse, (b) by formation of cracks or openings large enough to permit passage of flames or hot gases, and (c) by rise of temperature of the surface opposite to the fire exposure by more than 250°F on the average, or 325°F at any single point. Experience has shown (Abrams & Gustaferro 1968) that in standard fire tests of concrete floors or roofs, the fire endurance is determined most frequently by the criteria for temperature rise of the unexposed surface than by other criteria. The term "small-scale" fire test is generally used to denote tests conducted on specimens whose length and breadth are smaller than the minimum measurements prescribed by ASTM E-119. In this research, the cross-sectional dimension (thickness) of the small-scale specimen is not scaled down. Also, because the heat flow is perpendicular to the slab, this test can be considered a full-scale test. Experience over several years has shown that there is no significant difference in "thermal fire endurance"[1] obtained in the laboratory at the National Research Council in Canada by small-scale tests and by full-scale standard tests (Harmathy, 1966). However, because of the space, equipment and financial restrictions in this research, the 4-feet by 4-feet by 4-inches specimens were not

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[1] Thermal fire endurance means the time at which the temperature on one side of a test specimen exceeds its initial value by 250°F, average, or 325°F at any single point when the other side is exposed to a standard fire specified by ASTM E-119.

reinforced and no superimposed load was applied. Therefore, only the unexposed surface temperature criterion for thermal fire endurance was considered. The other criteria were ignored unless collapse or excessive cracking occurred before the unexposed surface temperature criterion was reached.

The absence of reinforcing bar may reduce the resistance to expansion and loading, and the absence of boundary constraints allows more bending due to thermal expansion. Both situations affect the concrete properties during a fire test.

To achieve the research goal of obtaining all needed data and performing a satisfactory statistical analysis, the sample size should be much larger than what was used in this research. Due to limited resources, such as manpower, equipment, time, and money, sample size could not be increased to a more satisfactory level for obtaining more desired data and for conducting a more complete statistical analysis.

Based on the works of Abrams and Gustaferro (1968) and Menzel (1943), the slab thickness, aggregate type, water/cement ratio, cement type, the moisture condition, and duration of drying affect the fire resistance rating significantly. However, all of these variables except moisture content were held constant in this research. The variables of interest in this research are the pre-exposure severity, re-curing method, and re-curing time lapse.

Due to the limitation of sample size, no core samples were drilled after the first fire exposure. Therefore, the actual residual compressive strength of the concrete from the slabs could not be obtained, which consequently makes the residual strength analysis incomplete. Although, theoretically, these strength could be estimated by interpolation by using the available data, it could not be done satisfactorily in this research due to the poor correlation between nondestructive and destructive test results was found.

CHAPTER 2
LITERATURE REVIEW

2.1 Fire Resistance, Fire Test, and Structural Fire Protection

A "fire-safe" building can be defined as one that has a low probability of fire occurrence and, if fire does occur, a high probability that all occupants will survive without injury and that property damage will be confined to the compartment in which the fire occurs. The minimum requirements for fire safety are dealt with, in law, by building codes.

Fire resistance, as defined by the American Society for Testing and Materials (ASTM E-176), is the property of a material or assemblage to withstand fire or give protection from fire. As applied to elements of buildings, it is characterized by the ability to confine a fire or to continue to perform a given structural function, or both. In contrast, fire endurance is the time period during which a material or construction assembly continues to exhibit fire resistance and to perform these functions when exposed to fire (Boring et al. 1981).

One key notion of building fire-safety design brought up by Campbell (1986) is that people and property not directly

exposed to a fire should be protected by confining heat and smoke to the area of origin until the fire either is extinguished or burns itself out. To be contained, a fire must be bounded by barriers that limit the transmission of heat and hot gases to combustible materials. Such barriers must maintain their continuity and stability under the thermal and physical forces of a fire.

The fire resistance of a structure is a function of the dimension of the structural elements and of the mechanical and thermal properties of the materials of which they are composed (Lie 1972). At present, the fire resistance of structural elements normally is determined by exposing certain surfaces of a test specimen to heating in a furnace so as to simulate its exposure to heat in a fire. The test specimen is usually a representative of the construction for which the classification is requested as to materials, dimension of elements, and workmanship. In some cases, however, when the materials are known and the shape and composition of the elements are not too complex (e.g., homogenous material), it is possible to determine their fire resistance by calculation (Lie 1972).

Floors and walls designed as fire separations have been recognized for many years as efficient tools in confining fire to the area of origin or limiting its spread. Prior to 1900, relative fire safety was achieved by mandating specific materials. By 1900, the appearance of many new materials and

innovative designs and constructions accelerated the demand for performance standards. The British Fire Prevention Committee, established in 1884, was the first to produce tables listing fire-resisting floors, ceilings, doors, and partitions (Bird & Docking 1949). Test furnaces for fire resistance testing in the United States were constructed shortly after 1900 at Underwriters Laboratory, Inc., Columbia University, and the National Bureau of Standards (NBS) (Babrauskas & Williamson 1978-79). These early test furnaces consequently led to the development of Test Method E-119.

Test Method E-119 was first published by the American Society for Testing and Materials (ASTM) as C 19 in 1918. A number of refinements have been made in the standards since that time. However, several provisions, including the time-temperature curve, the major apparatus, and the acceptance criteria, remain essentially unchanged.

For nearly the last nine decades in the United States, fire endurance design for buildings has been based on Standard E-119 of ASTM. The most widely used of these procedures are described in the ASTM-adopted "Standard Methods of Fire Tests of Building Construction and Materials." This test method is used to evaluate walls, partitions, beams, columns, floors, and roof assemblies. Similar procedures are used for determining the fire endurance of door and window assemblies.

Although the fire resistance test has been criticized for its various shortcomings, it is the only method universally

accepted in building codes today. In practice, there is a wide variation in the intensity rate of actual building fires. But the standard time-temperature curve does provide a basis for comparative purposes. Therefore, standard test methods were employed in this study as the preheating severity and fire resistance evaluation method.

2.2 Fire-load Concept of the ASTM Standard Test Methods

After the ASTM adopted the "Standard Specification for Fire Test of Materials and Construction" Fire Tests of Materials and Construction" as a standard test method in 1918, there was no accepted method for establishing the appropriate levels of fire endurance necessary for the structural components of buildings of different sizes and occupancies until the National Bureau of Standards (NBS) in 1922 undertook an ambitious program to investigate the nature of building fires. The first experiments to relate the results of furnace tests to fire conditions were conducted by Ingberg of NBS (Campbell 1986). The primary objective of this effort was to determine the intensity and duration of uncontrolled fires in certain occupancies resulting from different levels of fire load.[1] A second objective was to investigate the validity of

[1] Fire load is a measure of the heat content of the combustible materials present in a room. It is often defined as the heat content of the combustible materials per unit floor area. Fire load can also be considered as the total heat content of the combustible materials in an enclosure. In that case the heat content per unit area is called the fire load density.

the standard time-temperature curve (Boring et al. 1981). Ingberg simulated fire loads to be expected in offices, shops, warehouses, etc. and made an attempt to correlate the fire severities in these experiments to those experienced by similar construction elements in the furnace tests (Malhotra 1982).

Ingberg's (1942) major contribution to fire endurance theory consisted of recognizing a quantitative variable important in determining the expected fire, namely, the fire load. His burnout results indicated that the expected fires could have temperatures quite different from the standard curve. In support of the fire load theory, Ingberg organized fuel (fire) load surveys, the major results of which were reported in 1942 in Report BMS 92, which summarized some 25 years of fire endurance studies at NBS. If different building occupancies had different fire loads, which determined different time-temperature curves, then the direct consequence would be a multiplicity of fire resistance tests for an assembly using different curves. Ingberg realized the impracticality of that approach (Babrauskas & Williamson 1978/79). The simplest solution was to reduce the dimensionality of the problem from two, temperature and time, to one, "severity."[2] There was no physical basis for this

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[2] In the early studies the severity of a fire was thought to be related only to the calorific value of the combustible content of the building. Later studies have shown that the severity of a fire is often determined by the dimension of the openings through which air for combustion can be supplied and

simplification, so he provided a hypothesis: "What mattered was not the entire time-temperature curve but merely the integral under it." He defined this integral as the "severity" of the fire (Boring et al. 1981).

The first correlation between the fire severity and fire load density was found in this program. Also, it was the first time that test results from existing buildings were used to predict the fire resistance rating of prospective buildings. Based on the test results, it can be concluded that the standard time-temperature situation can be considered as a maximum severity of a building fire.

On the basis of the data collected from these experiments, it was suggested that a simple relationship could be established between the average weight of combustible materials within a room and the fire endurance necessary to withstand a complete burnout of the contents. This relationship, generally referred to as the "fire load concept," is shown in Table 2-1. In the simplest terms, the above assumption states that 10 lb of wood per square foot of floor area will produce a fire of 1 hour duration.

2.3 The Limitations of the Standard Fire Test

Based on theoretical and empirical research in applying the results of fire tests to actual building design during

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by the thermal properties of the walls/floors/ceilings. The mathematical meaning of fire severity is the total area under the Time-Temperature curve along with a certain time period.

Table 2-1: Relationship between fire load and fire endurance

Average Fire Load psf (kg/m²)*	Equivalent Fire Endurance (hours)
5 (24.4)	1/2
7½ (36.6)	3/4
10 (48.8)	1
15 (73.2)	1½
20 (97.6)	2
30 (146.5)	3
40 (195.3)	4½
50 (244.1)	6
60 (292.9)	7½

* Determined on the basis of weight of wood per square foot which has a potential heat of approximately 8000 Btu's per pound.

the last few decades, researchers have revealed several limitations inherent in the test procedures of standard fire resistance testing (Babrauskas & Williamson 1978; Harmathy 1979b; and Brannigan 1982):

1. fire resistance of columns is concerned with resisting collapse;
2. fire resistance of floors is concerned with passage of fire and collapse;
3. fire resistance of walls is concerned with passage of fire and collapse;
4. fire resistance of fire doors is concerned with passage of fire;
5. fire resistance is not specifically concerned with smoke control;
6. modern systems very often do not provide smoke containment;
7. most situations of standard tests are by no means common in actual fires; and
8. the agreement between different laboratories and the reproducibility of the characteristics of fully developed fires within the same laboratory are poor.

2.4 Properties of Concrete at High Temperatures

To understand the response of structures to the high temperatures experienced in fires it is important to have a

knowledge of the changes that occur in the properties of materials of which they are constructed. Most of this information for materials has become available during past several decades. The effects of temperature on concrete are described in this section.

2.4.1 General Review

Concrete is a composite material whose behavior is controlled by the aggregate and cement-paste interactive effects. It is, therefore, helpful to understand the effects of heating on these components.

2.4.1.1 Cement paste

Heating hardened cement paste causes removal of water by drying, by desorption, and by decomposition of hydrates. This removal of water causes shrinkage and changes in density, and it modifies the bonding forces between the minute crystals that comprise the cement gel. In this way, drying affects the dimensions, stiffness, and strength (Institute of Structural Engineers [ISE] 1975). The total amount of volume change of concrete is the sum of volume changes of the cement paste and aggregate. At high temperatures, the paste shrinks due to dehydration, while the aggregate expands. For normal aggregate concrete, the expansion of the aggregate exceeds the paste shrinkage, resulting in overall expansion of the concrete (Kosmatka & Panarese 1988).

For a modest rise in temperature, desorption of water leads to an increase in strength as the structure of the paste becomes more compact by drying. High-temperature exposure, however, causes decomposition and loss in strength in ordinary Portland cement pastes at temperatures above around 630°F.

The chemical changes that occur in cement paste during heating at high temperature cause changes in color that are characteristic of the exposure temperature. These color changes are therefore useful temperature indicators in investigating damage following a fire (Bessey 1950). However, the precise nature of the chemical changes that occur are not yet fully understood.

2.4.1.2 Aggregate

Because the fine and coarse aggregate generally occupy 60 - 75% of the concrete volume (70 - 85% by weight) (Kosmatka & Panarese 1988), the properties of concrete at high temperatures are strongly affected to some extent by the type of aggregate (Menzel 1943; Abrams & Gustaferro 1968; Abrams 1973; and Abrams 1977) including thermal expansion, Poisson's Ratio, creep, modulus of elasticity, strength, thermal conductivity, heat capacity, and thermal diffusivity. Most aggregates used in structural concretes can be classified into three types: carbonate, siliceous, and lightweight. Carbonate include limestone and dolomite, which are grouped together because they undergo chemical changes at temperatures in the

range of 1,200 - 1,500°F (Abrams 1973). Unlike the siliceous aggregates, limestone neither changes its physical composition nor undergoes sudden expansion during heating except at extremely high temperatures when the limestone ($CaCO_3$) is decomposed into lime (CaO) and carbon dioxide (CO_2). Because this reaction is endothermic and tends to retard the temperature rise in a concrete member made with limestone aggregate, it serves to extend the fire resistance period (ISE 1975). This benefit is paid for by the occurrence of damage after cooling when the free lime combines with atmospheric moisture to form calcium hydroxide, resulting in an increase in volume. Also, due to the absence of physical and chemical changes, conduction of heat within the concrete is controlled by the thermal diffusivity[3] of materials, while heat transfer at the surface is controlled by the surface conditions and thermal conductivity (ISE 1975).

The expansion of quartz is complicated by a number of physical changes that take place at high temperatures. The most well known of these is the transformation from α-form to β-form quartz that occurs at 1,060°F and which is accompanied by a 0.4% increase in volume (Abrams 1973). The relatively high thermal expansion of siliceous rocks and the abrupt volume change probably account for the decrease in compressive strength.

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[3] Thermal diffusivity, a, is related to thermal conductivity k, density ρ and specific heat c_p by $a = k / \rho c_p$.

Structural lightweight concrete has strengths in excess of about 2,500 psi and unit weights within the range of about of 90 to 115 pcf. Lightweight aggregates are manufactured by expanding shale, slate, clay, slag, or fly ash, or they occur naturally. The expanded shales, clays, and slates are heated from about 1,900 - 2,000°F during manufacturing. At these temperatures the aggregates become molten. As a result, such lightweight aggregates near the surface of concrete subjected to standard fire tests begin to soften after about four hours' of exposure. In most practical situations, this softening is not significant (Gustaferro 1974). The thermal conductivity of building materials generally is closely related to moisture content and dry density, the precise nature of the materials having only secondary significance. Because of this situation, lightweight aggregates give improved performance with respect to heat transmission in fire tests.

2.4.1.3 Concrete

Generally, maintaining temperatures greater than 200°F for several months or even several hours can cause significant effects on concrete. Thermal expansion is not a linear function of temperature but increases with increasing temperature. Some aggregates with low coefficients of expansion, such as expanded shale, andesite, or pumice, can produce a very volume-stable concrete at high temperature (see Figure 2-1) (Abrams 1977).

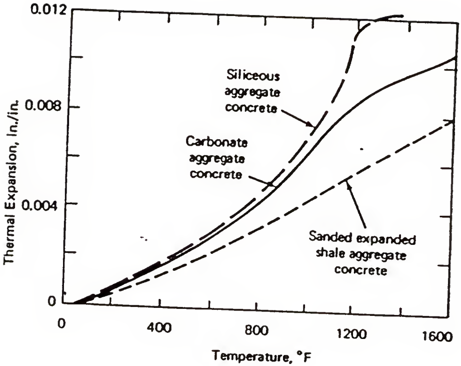

Figure 2-1: Thermal expansion of concrete at elevated temperatures (Abrams 1977)

Some aggregates undergo extensive and abrupt volume changes at a particular temperature, causing distress in concrete. For example, in Carette, Painter and Malhotra's (1982) study, a dolomitic limestone aggregate contained an iron sulfide impurity that caused severe expansion, cracking, and disintegration in concrete exposed to a temperature of 302°F, for four months; at temperatures below 302°F there was no detrimental expansion.

Figure 2-2 shows data on the strength of concrete at high temperatures (Abrams 1973). The data show strengths of concrete specimens stressed to 40% of their compressive strength during the heating period. After the test temperature was reached, the load on the specimen was increased until failure occurred. It can be noted that the strengths of carbonate and lightweight aggregate concretes are only slightly reduced at temperatures up to 1,200°F. The strength of siliceous aggregate concrete is reduced to about 55% at 1,200°F.

The modulus of elasticity of concrete is affected primarily by the same factors that influence its compressive strength. Cruz (1966) has examined the reduction in elasticity of three types of concrete. Figure 2-3 shows a steady elasticity reduction for all three types. Schneider (1976) obtained slightly more favorable results for lightweight aggregate concrete made with expanded clay. Anderberg's results are similar to Schneider's work and extend

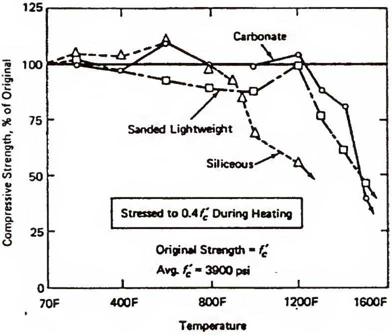

Figure 2-2: Compressive strength of concrete at high temperatures (Abrams 1973)

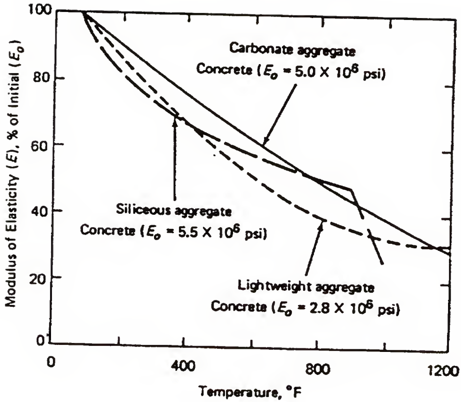

Figure 2-3: Modulus of elasticity of concrete at high temperatures (Cruz 1966)

to temperatures up to 1,472°F (Malhotra 1982).

Creep data in the conventional sense have little practical application to the behavior of concrete structures under fire conditions. They are obtained by heating specimens to a stabilized temperature, applying a load, and maintaining it at a constant value for days to achieve consistency of strain rate. In actual cases, structures are exposed to fires for only a few hours, and temperatures are rarely stabilized. Short-duration transient creep tests however can provide some useful information. Data on the basis of tests on gravel-aggregate concrete are shown in Figure 2-4 for reloaded specimens. These results show that up to a temperature of 752°F, creep is not significant for short-duration heating. It is affected by the level of the preload, which becomes significant at higher temperatures (Malhotra 1982).

A knowledge of the stress/strain characteristics of concrete is important in predicting its behavior in a fire test. Anderberg and Thelandersson (1976) examined characteristics of a number of concretes under various test conditions. Figure 2-5 shows data for gravel-aggregate concrete conditioned at 65% relative humidity and 68°F in which the specimens were not loaded during heating. Consequently, up to the temperature of 752°F, reduction in ultimate strength was small. With increasing temperatures, higher strains and lower ultimate stress were observed. These data give information not only on compressive strength but

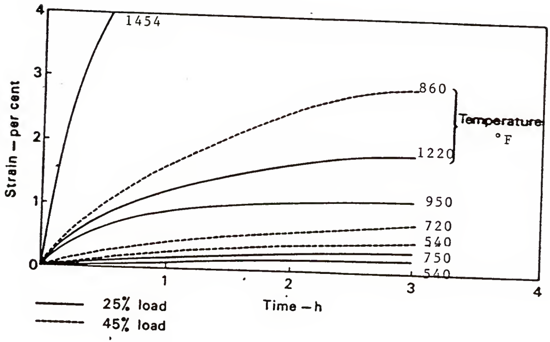

Figure 2-4: Short-duration creep tests with preload (dense concrete) (Malhotra 1982)

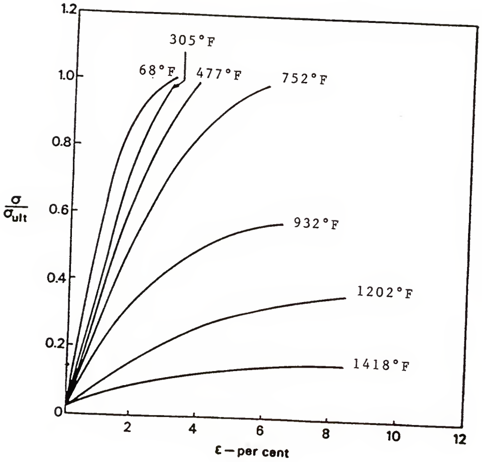

Figure 2-5: Stress/strain relationships for dense concrete (no preload -- method 1) (Anderberg & Thelandersson 1976)

also elasticity and ultimate strain. If, however, the strain rate is controlled during loading, higher strains result (Figure 2-6) with a decrease in stress in the descending part of the curves (Anderberg & Thelandersson 1976).

Thermal conductivity of concrete depends upon the nature of the aggregate, porosity of the concrete, and the moisture content. Since the moisture is driven out in fires, primary interest is in the conductivity of dry concrete. Harmathy (1970) has examined various concretes and obtained performance bands (Figure 2-7). It appears that for dense concretes, conductivity decreases with increasing temperature, but for lightweight aggregate concretes, the decrease is moderate. Other works have found similar trends, although the actual values tend to differ between investigations due to variations in materials and experimental techniques (Malhotra 1982).

2.4.2 Temperature within Concrete Slab During Fire Test

Figure 2-8 shows data on temperatures within solid concrete slabs exposed to a Standard Fire (ASTM E-119) on one side (Abrams & Gustaferro 1968). The curves in Figure 2-8 are applicable to slabs of any thickness, provided that the slab thickness is at least about 1 inch thicker than the curve in question.

A comparison of the temperatures within the silicious, carbonate, and sanded expended-shale aggregates is shown in Figure 2-9. At ½ hr, temperatures were somewhat higher in the

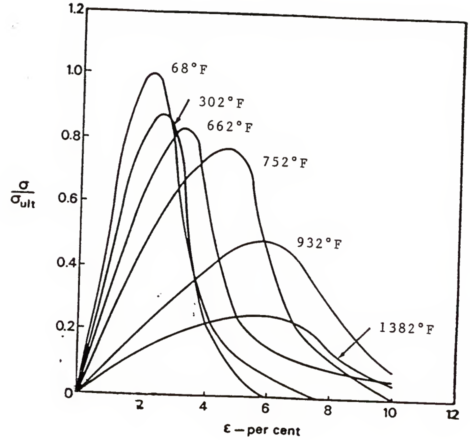

Figure 2-6: Stress/strain relationships for dense concrete (no preload -- method 2) (Anderberg and Thelandersson 1976)

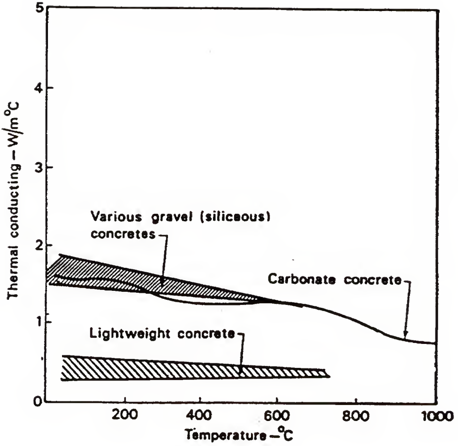

Figure 2-7: Effect of temperature on thermal conductivity of concrete (Harmathy 1970)

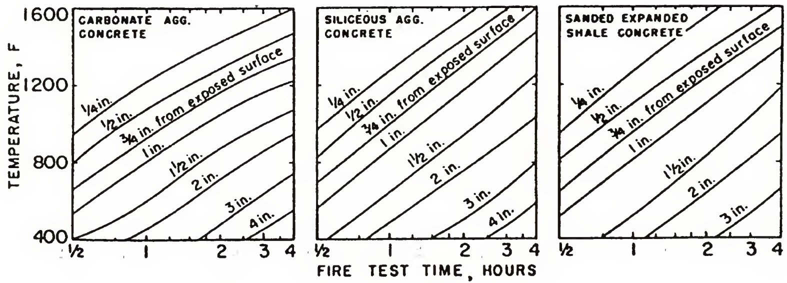

Figure 2-8: Temperatures within concrete during fire tests (naturally dried specimens)
(Abrams & Gustaferro 1968)

carbonate-aggregate concretes than in the sanded expended-shale concretes beyond 0.5 inch from the exposed surface, but the difference at any point was small. At 1½ hrs, comparing again the performance of the expended shale and carbonate slabs, temperatures at points beyond 1.2 inches from the heated surface were higher for the carbonate slabs, and temperatures near 1.2 inches were lower. At 4 hours, the dividing line was at about 2 inches. This behavior was probably the result of calcination of the carbonate aggregate (Abrams & Gustaferro 1968). Calcination occurs at temperatures above 1,365°F and is endothermic, i.e., heat is absorbed during the reaction. The same phenomenon was also discussed in several other research results (Menzel 1943; Selvaggio & Carlson 1964).

2.5 Nondestructive Test Methods

Because there are several disadvantages of destructive tests for concrete structures, such as specimens that must be loaded to failure, the delay in obtaining test results, the lack of reproducibility in the test results, and the relatively high cost of testing, there have been a large number of attempts over last 50 years to develop quick, inexpensive, reproducible methods such as nondestructive test methods to test concrete. Two nondestructive methods employed in this study are described below.

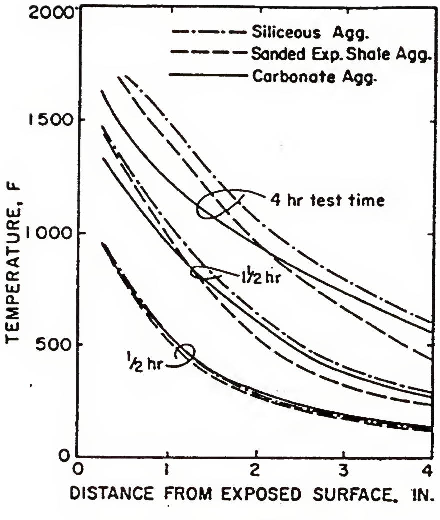

Figure 2-9: Comparison of temperatures within concrete slabs made with different aggregates (Abrams & Gustaferro 1968)

2.5.1 Schmidt Rebound Hammer

In 1948 a Swiss engineer, Ernst Schmidt, developed a test hammer for measuring the hardness of concrete by the rebound principle (Malhotra 1976). The Schmidt rebound hammer is basically a surface hardness tester. It consists of a spring-controlled hammer mass that slides on a plunger within a tubular housing. When the plunger is pressed against the surface of the concrete, it retracts against the force of the spring; when completely retracted, the spring is automatically released. The hammer impacts against the concrete and the spring-controlled mass rebounds, taking the rider with it along the guide scale. By pushing a button, the rider can be held in position to allow readings to be taken. These readings, rebound numbers, when translated to the chart on the hammer or in the handbook, give the compression resistance value with respect to the impact angle.

Based upon many works conducted in the last forty years, there is little apparent theoretical relationship between the strength of concrete and the rebound number of the hammer. Within limits, however, empirical correlations have been established between strength properties and the rebound number. According to Kolek (Kolek 1958) and Malhotra (Malhotra 1964), there is a general correlation between compressive strength of concrete and the hammer rebound number. There is, however, a wide degree of disagreement

among various studies concerning the accuracy of the estimation of strength from the rebound readings (Malhotra 1976). While the advantage of nondestructive test methods is still the main reason for using the Schmidt hammer, it serves as an auxiliary equipment to examine the correlation between rebound numbers and compressive strength of a concrete element exposed to fire.

2.5.2 Ultrasonic Pulse Velocity Meter

2.5.2.1 Introduction

The ultrasonic pulse velocity measurement is a method that is recognized as being able to determine the quality of the concrete in a structure through its entire thickness. This method, often used to assess damage of concrete exposed to fire, depends on information obtained from a "pulse-velocity" measurement through the concrete. The ultrasonic pulse velocity method was developed in Canada in 1945 by Leslie and Cheesman (1949), and at about the same time in England by Jones (Cheesman 1949; Jones 1957; and Jones 1962). These studies resulted in the development of an instrument known as the soniscope. Since then, a considerable amount of work has been reported on the use of this instrument both in Canada and in the United States. The apparatus developed in the 1940s made use of a cathode-ray oscilloscope for the measurement of transit times; and modified forms of this

equipment have been used widely in many countries (Malhotra 1976).

ASTM has had specifications in ASTM C-597 for the use of this method since 1967, and British Standards Institution issued recommendations for measurement of velocity of ultrasonic pulses in concrete under the British Standard title: B.S. 1881: Part 203, 1986.

2.5.2.2 Principles of ultrasonic pulse velocity measurement

The velocity of a mechanical impulse travelling in a solid material is almost independent of the geometry of the material they pass and depends only on the density and elastic properties of that material. The quality[4] of some materials is evidently related to their elastic stiffness; therefore, the measurement of impulse velocity in such materials can usually be used to indicate their quality as well as to determine their elastic properties. The pulse can be generated either by a hammer blow or by the use of an electroacoustic transducer. However, electroacoustic transducers are preferred because they provide more control on the type and frequency of the pulse generated. Materials which can be assessed by this method include concrete and timber.

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[4] Leslie and Cheesman (1949) have given the pulse velocity rating for different concrete qualities based on the strength, cracking, disintegration, chert in aggregate, and soft stone aggregate.

The ultrasonic pulse velocity measurement is a pass-through technique requiring a signal-transmitting transducer on one side of the test member, and a signal-receiving transducer directly opposite on the other side of the test member. Also required is calibration information on the relationship of the pulse-velocity to concrete compressive strength and the general condition of the concrete under investigation.

The pulse frequency used for testing concrete or timber is much lower than that used in metal testing. The higher the frequency, the narrower the beam of pulse propagation, but the greater the attenuation (or damping out) of the pulse vibrations. Normally, metal requires a high-frequency pulse to provide a narrow beam of energy, but such frequencies are unsuitable for use with heterogeneous materials because of the considerable amount of attenuation that pulses undergo when they pass through these materials. The frequencies suitable for the field testing of concrete range from about 20 kHz to 250 kHz. These frequencies correspond to wavelengths ranging from about 8 inches for the lower frequency to about 0.6 inches at the higher frequency (James Instruments, Inc. 1992).

2.5.2.3 Applications for fire-damaged concrete evaluation

Muenow and Abrams (1986) pointed out that there are some drawbacks that limit the usefulness of information obtained due to alignment of the transducers and to the too low pulse

velocity. However, several studies have reported very satisfactory results. Measurement of deterioration of concrete due to fire exposure had been established by Zoldners, Malhotra, and Wilson (1963) using pulse velocity techniques to measure deterioration caused by fire. In their investigation, they had exposed concrete prism (3½" X 4" X 16") specimens to fire for 1 hour at temperatures ranging of 212 - 2120°F. After the exposure, the specimens were removed from the furnace and allowed to cool to room temperature. Pulse velocity then was measured using an ultrasonic concrete tester; following this, the prisms were tested in flexure strength test machine. Figure 2-10 shows the results of one of these investigations. Zoldners et al. found that the deterioration in the prism specimens can be determined by measuring the percent loss in pulse velocity and that the percent loss in pulse velocity followed very closely the percent loss in flexural strength of test prisms after fire exposure.

Relationships between pulse velocity and compressive strength as determined by tests of cylindrical specimens has been compiled by many investigators. Plots of pulse velocity versus compressive strength from Watkey's (1955) and Rowe's (1981) investigations are presented in Figure 2-11 and 2-12, respectively. Figure 2-12 additionally presents a useful correlation obtained from pulse velocity tests to estimate the residual crushing strength of the concrete after fire. It

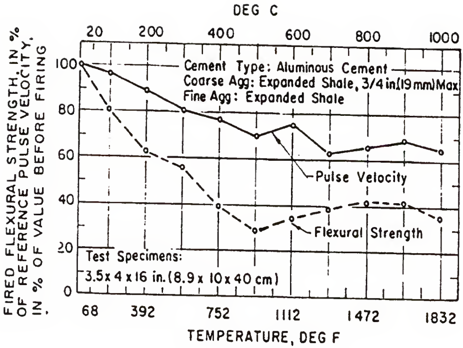

Figure 2-10: Loss in pulse velocity and flexural strength of concrete prisms after exposure to temperatures to 2120 °F (Zoldners, et al. 1963)

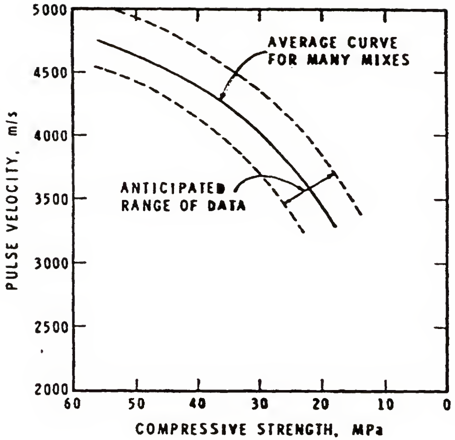

Figure 2-11: Pulse velocity vs. compressive strength relationship (Rowe 1981)

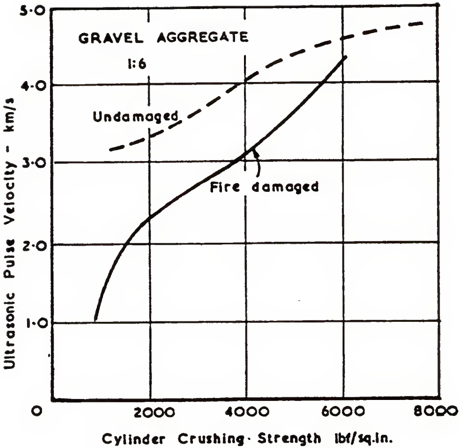

Figure 2-12: Curve relating residual strength with pulse velocity for concrete damaged by fire (Watkeys 1955)

apparently shows that, for a given residual strength, the pulse velocity was less than that for undamaged concrete.

More recently, Lie, Rowe, and Lin (1986) presented additional information on the relationship of pulse velocity and compressive strength for concrete control cylinders. This information is shown in Table 2-2.

Table 2-2: Average measured pulse velocity and compressive strength for 152 X 305 mm companion cylinders (Lie, et al. 1986)

Column	Cylinder No.	Average Pulse Velocity (ft/s)	Compressive Strength (psi)
A	1	14993.44	5466.5
A	2	15091.86	5655
A	3	15141.08	5800
B	1	15305.12	6104.5

CHAPTER 3
TEST DEVELOPMENT

This chapter describes the requirements and standards of the experimental test program consisting of a small-scale fire test, two nondestructive tests, and a destructive test. Specimen preparation and experimental procedures also are presented.

3.1 Fire Endurance Test (ASTM E-119)

The purpose of this study is to investigate how the external factors affect the fire resistive ability of burned concrete. The problems studies studied included: (a) Can we determine intensity and duration of a fire that has occurred in a structure?; (b) Can the concrete strength be regained or grow with time after fire?; and (c) How does the re-absorption of moisture in the concrete affect the fire endurance? The three main-factors (i.e., pre-exposure severity, re-curing method, and re-curing time lapse) treatments were studied in a 2 X 2 X 2 factorial experimental design.

The first treatment, pre-exposure severity, was simulated in accordance with the ASTM E-119 standard temperature curve. The exposure time periods were selected as ⅓ and ⅔ of the

average fire endurance of concrete slabs in the control group[1] to create two different heat impacts to the concrete slabs in the experimental groups. For convenience of instrument control, the exposure time periods were fixed at 30 minutes and 60 minutes. The second treatment, re-curing method (i.e., re-storing environment) was designed to expose the concrete slabs to different environments with different moisture conditions after fire exposure. The third treatment, re-curing time lapse, was designed to store the pre-burned concrete slabs for a time lapse of 30 days and 75 days.[2]

In this research, the standard fire exposure defined in ASTM E-119 was used for the pre-exposure severity and the fire test. This standard time-temperature curve is the only fire exposure accepted by code authorities in the United States to be used to simulate real fire intensity in buildings. The scope of "Standard Test Methods for Fire Tests of Building Construction and Materials" is intended to evaluate fire resistance in terms of endurance time (the ability of an assembly to contain a fire or to retain its structural integrity, or both, when subjected to the test conditions) by

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[1] Three concrete slabs were selected randomly as a control group which did not receive pre-exposed treatment. The average fire endurance of control group is 104.4 minutes.

[2] It is known (Lie 1972) that the modulus of elasticity of concrete which relates to the compressive strength will recover substantially with time. If concrete has not been heated above 930°F, most concrete specimen regain the modulus of elasticity in one month after fire exposure and can recover about 45% (heated to 930°F) to 93% (heated to 390°F) of its original value after twelve months.

measuring the heat transfer through membrane elements protecting combustible framing or surface. This standard also prescribes an exposing fire of controlled extent and severity, to be applied to a representative specimen of the building being tested.

The end-point criteria by which the test results are assessed are related to:

1. transmission of heat through the test assembly;
2. ability of the test assembly to withstand the transmission of flames or gases hot enough to ignite combustible material; and
3. ability of the assembly to carry the load and withstand restraining forces during the fire test period.

Based upon the discussion in preceding chapters, only the heat transmission criterion[3] was considered for determining the fire endurance in this research.

Table 3-1 shows some of the requirements for fire resistance ratings that appear in model building codes. For simplicity, only certain values are shown and qualifying statements have been omitted.

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[3] Since (a) the thickness of the test specimen is not scaled down, (b) the heat flow in the test furnace is perpendicular to the specimen, and (c) there is no significant difference in "thermal fire endurance" obtained in a test laboratory by small-scale tests and by full-scale standard tests, only the heat transmission criterion was considered in this study.

Table 3-1: Typical fire resistance rating requirements in Model Building Codes

Structural Element	Type of Construction			Model Code
	Highest Fire Resistive	2nd Highest Fire Resistive	Highest Non-Combustible	
Columns-supporting more than one floor	4 hrs 4 hrs 4 hrs 3 hrs	3 hrs 3 hrs 3 hrs 2 hrs	1 hr 2 hrs 2 hrs 1 hr	National Basic Southern Uniform
Girders, Beams, and Trusses	4 hrs 4 hrs 4 hrs 3 hrs	3 hrs 3 hrs 3 hrs 2 hrs	1 hr 2 hrs 2 hrs 1 hr	National Basic Southern Uniform
Floors	3 hrs 3 hrs 2.5 hrs 2 hrs	2 hrs 2 hrs 1.5 hrs 2 hrs	1 hr 1.5 hrs N.C.* 1 hr	National Basic Southern Uniform
Roofs	2 hrs 2 hrs 1.5 hrs 2 hrs	1.5 hrs 1.5 hrs 1 hr 1 hr	1 hr ¾ hr N.C.* 1 HR	National Basic Southern Uniform

* Noncombustible

3.1.1 Test Furnace

It should be recognized that the primary purpose of the ASTM Methods E-119 furnace is to provide a reproducible fire exposure for testing the fire endurance of specimens of building elements. The important consideration is reproducibility of this specific but arbitrarily selected (Babrauskas & Williamson 1978/79, Gustaferro 1974) fire exposure.

Because ASTM E-119 does not provide specific construction details of the furnace, a survey was conducted for information about the small-scale furnace design at the University of California (Berkeley), Underwriters Laboratory, Portland Cement Association, Southwest Research Institute, and the National Institute of Standards and Technology. All of the furnaces were of different design and certain features of each furnace were incorporated into the unit developed for this study. The construction of the furnace is discussed in Chapter 4.

3.1.2 Time-Temperature Curve

ASTM E-119 standard time-temperature curve shown in Figure 3-1 was used in the fire test. Some characteristics on the curve are listed in Table 3-2.

Based on the requirements prescribed in section 5 of ASTM E-119, the furnace temperature fixed by the curve shall be deemed to be the average temperature obtained from the

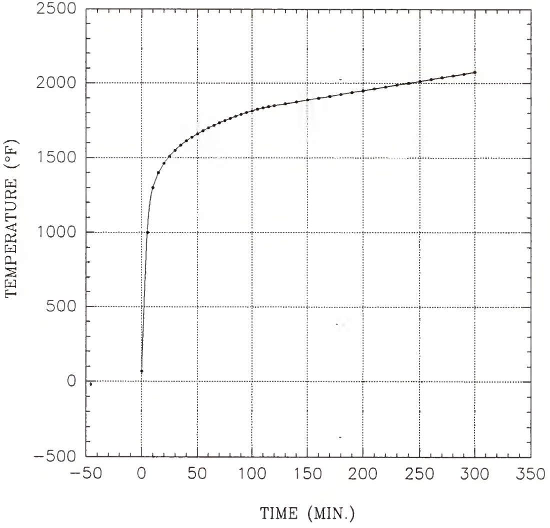

Figure 3-1: ASTM E-119 Standard time-temperature curve

Table 3-2: The characteristic points of Standard Time-Temperature curve

1,000°F (538°C)	at 5 minutes
1,300°F (704°C)	at 10 minutes
1,550°F (834°C)	at 30 minutes
1,700°F (927°C)	at 1 hour
1,850°F (1,010°C)	at 2 hours
2,000°F (1,093°C)	at 4 hours
2,300°F (1,260°C)	at 8 hours and over

readings of not less than nine thermocouples for a floor, roof, wall, or partition and not less than eight thermocouples for a structural column symmetrically disposed and distributed to show the temperature near all parts of the sample. In this research, due to the small volume of the furnace (i.e., 4 feet by 4 feet by 4 feet), the average temperature was obtained from the readings of three type K thermocouples which were located uniformly within the chamber. Additional temperature readings from one type R thermocouple were used to feed an analog signal to the "512 Process Controller." The exposed length of all thermocouples met the standard requirement of not less than 12 inches. All the junctions of the thermocouples were placed at least 4 feet away from the exposed face during the entire test procedure and did not touch the concrete slab as a result of its deflection.

Based upon the capability of the hardware and software designed for the temperature recording system, the furnace temperatures were read at 30-second intervals (ASTM E-119 requires reading intervals not exceeding 5 minutes during the first 2 hours, and 10 minutes after 2 hours).

ASTM E-119 requires that the accuracy of furnace control shall be such that the area under the time-temperature curve, obtained by averaging the results from the pyrometer readings, is within 10% of the corresponding area under the standard time-temperature curve shown in Figure 3-1 for fire tests of 1 hour or less duration, within 7.5% for those over 1 hour and

not more than 2 hours, and within 5% for these exceeding 2 hours in duration (ASTM E-119-88). Figure 3-2 shows the furnace temperature curves recorded during the last 43 fire tests. All of the curves fall into the temperature-tolerance band specified in the ASTM E-119 standard.

3.1.3 Temperatures on Unexposed Surface of Test Specimen

The standard fire test method limits the average temperature rise of the unexposed surface of floors, roofs, and walls to 250°F. Some building codes modify this requirement. For example, the National Building Code of Canada waives the temperature rise criteria for roofs. The Wisconsin State Building Code reduces the fire endurance requirement determined by heat transmission (i.e., 250°F rise) to half that required for structural integrity for many occupancies (Gustaferro 1974). For concrete assemblies, this temperature rise depends mainly upon the thickness and unit weight[4] of the concrete, but it is also influenced by aggregate type, concrete moisture condition, air content, maximum aggregate size, and aggregate moisture content at time of mixing (Menzel 1943; Abrams & Gustaferro 1968). Figure 3-3 shows typical unexposed surface temperatures recorded during

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[4] Conventional concrete, normally used in pavements, buildings, and other structures, has a unit weight in the range of 140 - 150 lb per cubic foot (pcf). The unit weight (density) of concrete varies, depending on the amount and the relative density of the aggregate, the amount of air that is entrapped, and the water and cement contents (Kosmatka & Panarese 1988).

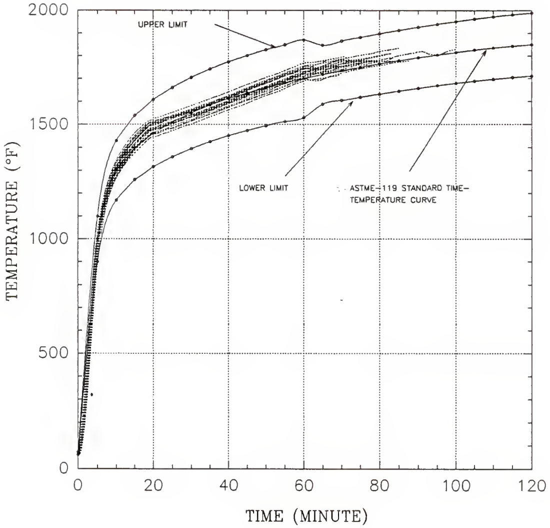

Figure 3-2: Furnace atmosphere temperatures recorded during 43 fire tests

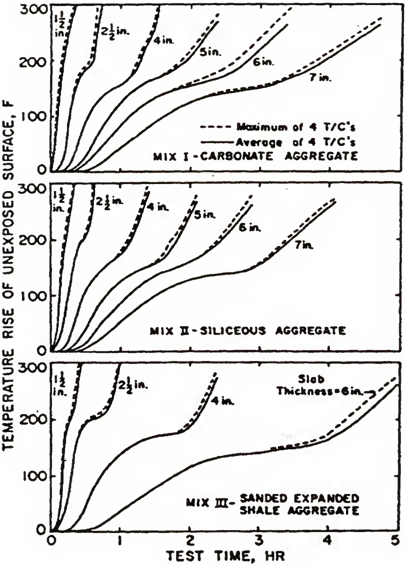

Figure 3-3: Temperature rise of unexposed surface during fire test (natural dried specimens) (Abrams & Gustaferro 1968)

standard fire tests (Abrams & Gustaferro 1968). The data in Figure 3-3 can be used to determine the fire endurance of concrete slabs as affected by the temperature rise of the unexposed surface. Figure 3-4 shows the relationship between slab thickness and fire endurance for a wide range of structural concretes (Abrams & Gustaferro 1968; Gustaferro 1970).

The fire endurance of the specimen was determined by the temperature rise of the unexposed surface, i.e., 250°F average rise or 325°F rise at any single point, whichever occurred first. Temperatures at four different locations on the unexposed surface of each specimen were measured with thermocouples that were placed under coverings measuring 6 inches by 6 inches by ½ inch of dry, flatted refractory fiber pad that met the specifications listed in Annex A1 in ASTM E-119. The hot junction of the thermocouple was placed approximately under the center of the pad and forced to contact the unexposed surface firmly by holding the pad against the surface with a small piece of refractory brick. The wire leads of the thermocouple were placed under the pad at least 4.5 inches.

Because of the small area of the concrete slab (16 ft^2), the temperature readings were taken from four points on the unexposed surface. One point was located at the center of the specimen and three points were located along the diagonals at approximately the center of the quarter section. No reading

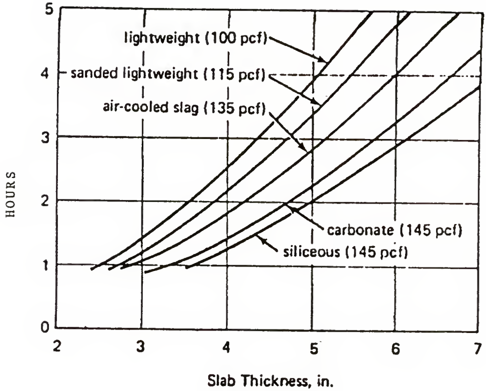

Figure 3-4: Effect of slab thickness and aggregate type on fire endurance of concrete slabs, based on 250°F rise of unexposed surface (Abrams & Gustaferro 1968)

was taken in the section containing the two groups of internal thermocouples[5] (see Figure 3-5). None of the thermocouples were located nearer to the edges of the test specimen than one and one-half times the thickness, 6 inches, of the construction. Temperature readings from the thermocouples on the unexposed surface and in the internal locations were taken at the same sampling rate devised for furnace temperature recording time interval, 30 seconds.[6]

3.1.4 Temperature within Test Specimen

Two grouped internal thermocouples were installed in one of the quarter sections of each test specimen for measuring the temperature within the concrete slab during the fire test (see Figure 3-5). Each group consisted of three thermocouples located at various elevations from the bottom side (exposed surface) of the test specimen: 1 inch, 2 inches, and 3 inches. Each hot junction of thermocouple was fixed tightly on one no.

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[5] Based on communication with T.T. Lie on May 20, 1992, normally, the acceptable difference between maximum and minimum measurements of unexposed surface temperature rise measuring is about 50°F. If the difference is above this range, the possible causes are: (a) insulation effects of thermocouple pad, (b) surface situation of the test specimen, (c) characteristics of test material, and (d) thickness of the test specimen. Also, in Canada no pad is required, therefore, it usually does not happen as often as in the United States.

[6] ASTM E-119 requires that the temperature readings shall be taken at intervals not exceeding 15 minutes until a reading exceeding 212°F (100°C) has been obtained at any one point. Thereafter the readings may be taken more frequently at the discretion of the testing body is measured. But the interval readings need not be less than 5 minutes.

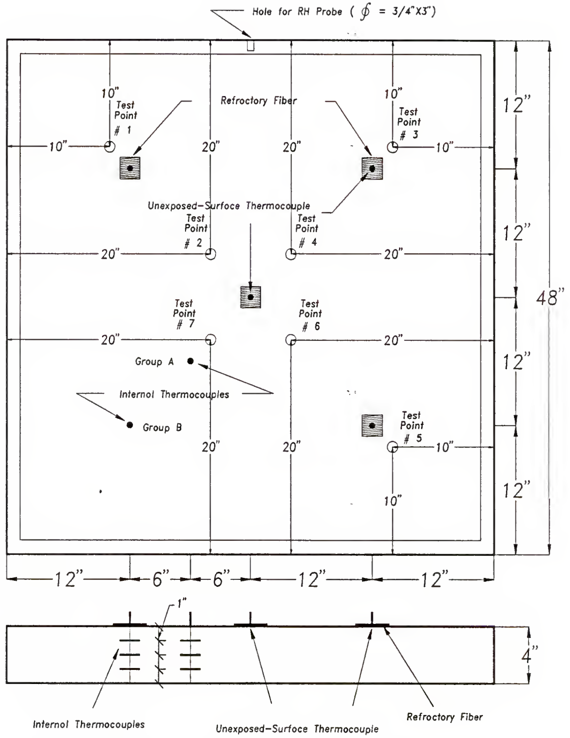

Figure 3-5: Locations of unexposed surface thermocouples, internal thermocouples, and seven test points

12 gauge steel wire which was screwed onto the connected edge boards of the formwork. The precise elevation of each thermocouple was measured prior to concrete casting for use in establishing thermal gradients.

3.1.5 Test Specimen

Fire tests were conducted on concrete slabs measuring 4 feet by 4 feet by 4 inches. Based upon the discussion in Chapter 1, the area of slab specimen would not affect the test results. In this study, it was of interest to determine whether or not the different level of pre-exposure severities, re-curing methods, and re-curing time lapses will affect the residual fire endurance of burned concrete structural elements. It is desirable to hold constant the variables of aggregate type, cement type, water/cement ratio, and maximum size of aggregate in the test specimens. By holding these factors constant, their possible effect on the results was eliminated from consideration. Therefore, the concrete specimens in this investigation were made with the same batch of ready-mixed concrete.

The specifications of ready-mixed concrete for 1 cubic yard batch were (#030315) are as follows:

1. Cement: Type I Portland Cement, 354 lb (about 6.67% by volume).
2. Aggregate:

   a. Coarse aggregate: Typical Florida limestone, 3/4-in. maximum-size containing some crushed particles, 1787 lb.
   b. Fine aggregate: Natural sand with an oven-dry specific gravity of 2.4 to 2.9 and maximum fineness modulus of 2.8, 1324 lb.
3. Fly ash: 88 lb.
4. Admixture:
   a. 961R: 14 o.z.
   b. M.B.UR: 1.77 o.z. (air-entraining)
5. Water: 191.97 lb.
6. Slump: 3 inches.
7. Design Strength: 3000 psi at 28-day cure.

3.1.6 Moisture Control of Test Specimen

It is known that the moisture condition of the concrete is an important factor affecting fire endurance and spalling. In general, fire test specifications require that, prior to testing, a specimen should be conditioned in order to bring its mechanical strength and moisture content as close as possible to that expected in service. Usually, moisture increases the fire resistance of a specimen but it causes spalling and its effect on fire resistance may be disadvantageous. If the concrete specimen spalls during the first fire exposure, it will be useless to conduct the residual fire endurance test.

Harmathy's (1961) theoretical studies indicated that, for a given material and geometry of construction, the fraction gain[7] in fire endurance in relation to the fire endurance in oven-dry condition is proportional to the volumetric moisture content.[8] The percentage gain[9] in fire endurance due to one percent moisture (by volume), called "figure of merit of moisture," is approximately constant for a specified construction. In later experimental works (Harmathy 1966), fire tests were conducted on 15 small-scale (30 inches by 30 inches) concrete slabs treated under different moisture conditions and some specimens were subjected to more than one fire test. Harmathy found that "figure of merit of moisture," Ψ, increases with the permeability, ν, of the materials, while it decreases slightly with the increase of τ_d. He summarized that concrete specimens yield 6 to 19 percent higher fire endurance in the first runs than in subsequent runs. Consequently, those test results were adopted by ASTM E-119 as an appendix, "Correcting Fire Endurance for Concrete Slabs Determined by Unexposed Surface Temperature Rise for Nonstandard Moisture Content."

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[7] Fractional gain is related to fire endurance at moisture content ϕ, τ_ϕ (hr) and fire endurance in oven-dry condition, τ_d (hr) by the form $(\tau_\phi - \tau_d)/\tau_d$.

[8] ϕ = volumetric moisture content, cu ft/cu ft.

[9] The percentage gain can be expressed as follows:

$$\psi = \frac{(\tau_\phi - \tau_d)}{\tau_d \phi}$$

During the same period, Abrams and Gustaferro (1968) found that some kiln-dried specimens contained less moisture than naturally dried specimens. This finding resulted even though their mid-depth relative humidities were the same and less heat was required to vaporize the moisture in kiln-dried specimens. For this reason, the unexposed surface temperature rose more rapidly and the endurance period was shorter.

The rather explosive breaking off of pieces from concrete during fire exposure is known as spalling. Lie (1972) concluded that, in general, spalling reduces the fire resistance of a structure. Sometimes it caused sudden loss of fire resistance because spalling may cause formation of holes and, as a consequence, loss of fire resistance. One other situation that should be noticed is that spalling of reinforced or prestressed structures may lead to direct exposure of the steel to the fire and reduction of the fire resistance of the structure. Spalling is often accompanied by loud bangs, and fragments of the material may be scattered to a distance of several feet.

Even though a number of detailed studies have been carried out, the precise nature of the complex phenomenon responsible for spalling is still not completely understood (Malhotra 1982). Simply speaking, spalling is relative to the nature of the aggregate, porosity of the concrete, its moisture content, and the stress level to which the concrete is subjected to. In siliceous aggregate concretes, moisture

content in excess of 2% by weight, section thickness below 2.76 inches (70mm), and rapidly changing temperature could induce spalling (Malhotra 1982). In the United States, a study was conducted to investigate concrete spalling at elevated temperature by J. P. Thompson in 1963. Thompson (1963) found that excessive moisture in the concrete at the time of fire testing was the primary cause of spalling. A method was developed in this research to indicate the internal moisture condition by measuring the relative humidity of air in contact with the interior of the concrete. It was found that when the moisture content of concrete was at equilibrium with the air, spalling did not occur.

Dougill (1972) has shown that explosive spalling[10] is a complex reaction generated by the development of high vapor pressures in the pores of a concrete section, causing cracks to be formed internally in a plane parallel to the surface. Under unfavorable stress conditions, the exposed concrete layers are blown away with explosive force. Such an occurrence can cause extensive damage and can substantially lower the fire resistance of the structural elements.

Based on the requirements in section 11 of ASTM E-119, for purposes of standardization, the moisture condition of

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[10] Malhotra classified spalling into two categories: (1) aggregate splitting: the bursting and splitting of silica containing aggregates due to physical changes in the crystalline structure at high temperature; (2) large or small piece of concrete are violently pushed off the surface accompanied by loud noises.

test specimen is to be considered as that which would be established at equilibrium resulting from drying in an ambient atmosphere of 50% RH at 73°F. However, with some constructions, it may be difficult or impossible to achieve such uniformity within a reasonable period of time. In this case, specimen may be tested when the dampest portion of the structure has achieved a moisture content corresponding to drying to equilibrium with air maintained at 50 - 75% RH at the temperature of 73 ± 5°F prior to the fire test. According to the results of some studies (Abrams & Gustaferro 1968; Menzel 1943; Abrams & Orals 1964; and Abrams 1973), the concrete specimens to be tested are all well-dried to moisture content of 70% RH or less at room temperature. If the construction elements contain more than 5% volume of Portland cement paste, the ASTM E-119 gives a procedure to correct the fire endurance of the concrete slab when moisture content at the time of test is other than at standard moisture levels (see appendix X4 in ASTM E-119 standard).

The procedures used for controlling the moisture content in this research can be summarized as follows:

1. Prior to the fire test, all concrete slabs, which had been moisture cured for 28 days, were moved into the drying room which was maintained at 7.5 ± 1.5% RH and at a temperature 142 ± 6°F. Figure 3-6 shows the location of each concrete specimen in the drying room.

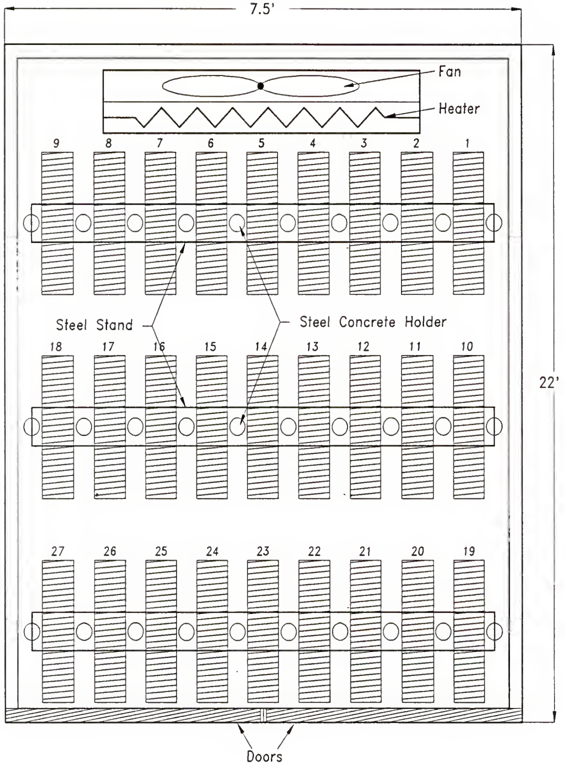

Figure 3-6: Locations of concrete specimens in the drying room

2. Drill one measuring well (¾" diameter X 3" deep for the VAISALA Model 1558 HM probe protection tube which is sealed until the time of measuring) at the mid-depth of middle position of one edge of each slab (see Figure 3-5) before moving the concrete slab into the drying room.
3. Measure the relative humidity[11] of each concrete slab by using VAISALA's HMI 31 indicator and HMP 36 humidity and temperature probe until the RH level within the concrete slab reaches 70% or less. Table 3-3 shows the relative humidity level of each concrete specimen at 50 days after moving into drying room and prior to the first firing.

3.2 Nondestructive Tests

Evaluation of fire-damaged concrete has been performed by using different test techniques which are valuable but limited data are available (Kordina et al. 1986; Lie et al. 1986; Muenow & Abrams 1986; Tovey 1986; and Sansalone & Carino 1988). Several nondestructive test methods have been developed for locating defects in concrete and estimating concrete compressive strength (Muenow & Abrams 1986). With

[11] Before measuring the relative humidity, the heater in the drying room was shut down at least 48 hours to let the concrete specimens cool down to room temperature. The probe was inserted into the sealed well for at least 1 minute to let the moisture of the air in the inside chamber reach equilibrium.

Table 3-3: Relative humidity level of concrete slabs

Specimen No. before Selection	Specimen No. after Selection	Moisture Content & Temperature 50 days after moving into Drying Room		Moisture Content & Temperature Prior to 1st Firing	
		Temperature (°F)*	Relative Humidity (%)**	Temperature (°F)*	Relative Humidity (%)**
1	TR_{000}-C	74.0	41.2	67.5	44.2
8	TR_{112}-C	78.4	76.0	74.9	53.8
8	TR_{212}-C	81.6	80.6	67.3	42.2
4	TR_{122}-C	81.6	42.1	73.2	46.0
5	TR_{222}-C	31.6	41.2	60.7	46.0
6	TR_{111}-C	80.1	34.1	71.5	48.5
8	TR_{211}-C	81.6	41.2	74.9	46.0
8	TR_{221}-C	81.6	81.6	74.9	48.5
9	TR_{121}-C	79.9	42.7	76.0	56.4
12	TR_{000}-B	81.6	81.6	74.7	49.6
11	TR_{112}-B	81.2	23.6	66.4	31.1
12	TR_{212}-B	81.6	32.2	59.5	46.0
19	TR_{122}-B	81.6	41.2	73.0	42.2
16	TR_{222}-B	81.6	80.1	59.5	47.6
15	TR_{111}-B	81.2	45.5	66.3	49.6
16	TR_{211}-B	80.7	42.0	72.5	55.1
17	TR_{221}-B	81.7	31.6	68.6	49.7
12	TR_{121}-B	80.7	38.4	71.0	55.1
19	TR_{000}-A	81.7	41.6	73.2	38.5
20	TR_{112}-A	80.6	44.7	66.3	29.7
21	TR_{212}-A	80.9	51.1	71.3	31.5
22	TR_{122}-A	80.9	43.5	72.9	58.0
23	TR_{222}-A	80.7	53.4	48.6	49.1
24	TR_{111}-A	81.2	46.4	65.4	51.1
25	TR_{211}-A	80.5	51.7	76.9	58.3
26	TR_{221}-A	79.6	40.2	70.6	47.3
27	TR_{121}-A	80.7	41.1	66.1	49.1

* Temperature accuracy at +68°F: ±0.54°F in range -40°F to +176°F

** Humidity accuracy at +68°F: ±2%RH in range 0 to 90%RH, ±3% in range 90 to 100%

the advantage of nondestructive testing methods, a much more simple and comprehensive evaluation of damage is possible. Two kinds of nondestructive tests were employed in this research to evaluate the fire damage conditions of concrete slabs.

3.2.1 Schmidt Rebound Hammer Test (ASTM C-805)

3.2.1.1 Scope and use

ASTM C-805 recommends that the rebound hammer be used to assess the uniformity of concrete in situ, to describe zones or regions of poor-quality or deteriorated concrete in structures, and to indicate changes with time in characteristics of concrete such as those caused by the hydration of cement. The ASTM C-805 standard insists that this test method is not intended as an alternative for strength determination of concrete. However, the rebound hammer can be most useful for rapidly surveying large areas of similar concrete in the construction under study if the correlation with the core testing information is well established by laboratory calibration.

One notion should be recognized before this method is used to evaluate the compressive strength of concrete elements. Malhotra (1976) indicated that there is a wide degree of disagreement among various researchers concerning the accuracy of the estimation of strength from the rebound readings. Coefficients of variation for compressive strength

for a wide variety of specimens averaged 18.8 percent and exceeded 30 percent[12] for some groups of specimens. By consensus, the probable accuracy of prediction of concrete strength in a structure is ± 25% while it can be found between ± 15 and ± 20% under well-controlled laboratory conditions.

For in-situ application, Făcăoaru (Făcăoaru 1969) suggested a combined method based on rebound number and pulse velocity measurements. Teodoru (Teodoru 1989) provided a further application based on a linear model using a computational program performing a step-by-step analysis to establish the correlations between nondestructive measured values (ultrasonic pulse velocity and rebound hammer) and the compressive strength of concrete.

3.2.1.2 Apparatus

The model C 181, type N, concrete rebound hammer used in this research was made by CONTROLS® S.p.A. in Italy. It consists of a spring-loaded steel hammer which, when released, strikes a steel plunger in contact with the concrete surface. The spring-loaded hammer travels with fixed and reproducible velocity. The rebound distance of the steel hammer from the steel plunger is measured on a linear scale attached to the frame of the instrument.

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[12] Malhotra suggested that this large deviation in strength can be narrowed down considerably by proper calibration of the hammer.

3.2.1.3 Test locations and method

Although the rebound hammer provides a quick, inexpensive means of checking uniformity of concrete, there are several limitations that must be recognized before this method is employed for in situ application. The results of the Schmidt hammer are affected by (Malhotra 1976):

1. Smoothness of surface under test.
2. Size, shape, and rigidity of the specimen.
3. Age of test specimen.
4. Surface and internal moisture condition of concrete.
5. Type of coarse aggregate.
6. Type of cement.
7. Type of mold.
8. Carbonation of concrete surface.

In this study, for understanding how the rebound number was affected by the fire exposure, seven points were selected on the unexposed surface[13] of each concrete specimen (see Figure 3-5). The Schmidt rebound hammer was applied at each point prior to first firing, prior to second firing, and after second firing. All the specimens were under the same experimental factorial design model as the residual fire

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[13] Since the exposed surface of test specimen was too fragile to withstand the impact of rebound hammer after each firing, the test points were selected on the unexposed surface.

resistance rating test. The differences of the three rebound numbers at same test point were correlated with the concrete fire damage situation. These tests and the three different factors (i.e., pre-exposure severity, re-curing method, and re-curing time lapse) were analyzed to determine how they affected the test results. By using this measuring method and concentrating on differences rather than actual readings, the variety of variables effecting the test results as discussed early can be disregarded.

The determination of the hammer rebound is a simple procedure and is outlined in the manual supplied by the manufacturer. Briefly, the procedure consists of releasing the plunger from the locked position by pressing it gently against a hard surface. The hammer is then ready for use. To carry out the test, the plunger is pressed strongly against the concrete surface under test. This pressure releases the spring-loaded weight from its locked position, thus causing an impact. While the hammer is still in its testing position, the sliding index is read to the nearest whole number. The reading is designated as the hammer number. The readings were recorded for each test point.

3.2.2 Ultrasonic Pulse Velocity Test (ASTM C 597)

3.2.2.1 Scope and use

The test method in ASTM C-597 titled "Standard Test Method for Pulse Velocity Through Concrete" can be used to

determine the pulse velocity of propagation of compressional waves in concrete. The pulse velocity is independent of the dimensions of the body provided the reflected waves from boundaries do not complicate the determination of the arrival time of the directly transmitted pulse. The pulse velocity V is related to the physical properties of a solid by the equation:

$$V^2 = (K)\frac{E}{D}$$

where:

K = a constant,

E = the modulus of elasticity, and

D = the density.

The relationship is independent of the frequency of the vibrations.

ASTM Ç-597 standard recommends that the pulse velocity test meter can be used to advantage to assess the uniformity and relative quality of concrete, to indicate the presence of voids and cracks, to estimate the depth of cracks, to indicate changes in the properties of concrete, and in the survey of structures to estimate the severity of deterioration or cracking.

The path length between transducers divided by the time of travel gives the average velocity of wave propagation. Path length and transit times are generally measured to an

accuracy of about ± 1 percent (Malhotra 1976). The basis for the estimation of the pulse velocity traveling through the concrete slab was established by measuring the velocity of the ultrasonic pulse generated by the V-meter transmitted from one end to the another end of the concrete core sample taken from two additional concrete slabs numbered Tr_{999}-A and Tr_{999}-B. These two slabs were made from the same batch of ready-mixed concrete as all test specimens. When the mid-depth of each slab reached the moisture content criterion, equal to or less than 70% RH, after the slabs had been in the drying room, four core samples were taken from each concrete slab. The exact length of each core sample was measured prior to the ultrasonic pulse velocity test. Table 3-4 shows the velocity of ultrasonic pulse traveling through the concrete core samples. The average ultrasonic pulse velocity is about 14,519.3 feet per second for this ready-mixed concrete.

3.2.2.2 Apparatus

The testing apparatus required by ASTM C-597 is shown schematically in Figure 3-7. The ultrasonic pulse velocity tester, V-meter, employed in this study was made by James Instruments Inc. in Chicago, Illinois. The V-meter was designed for site testing and generates low frequency[14] ultrasonic pulses and it measures the time taken for the

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[14] 50 kHz frequency is appropriate for field testing of concrete.

Table 3-4: Velocities of ultrasonic pulse traveling through concrete core sample

Specimen		Length (in.)	Pulse Travel Time (μs)	Pulse Velocity (ft/s)
Tr_{999}-A	1	4.03	23.8	14,110.6
	2	4.15	24.8	14,045.7
	3	4.13	24.6	13,990.5
	4	4.15	24.6	14,058.3
Tr_{999}-B	1	3.99	22.1	15,045.3
	2	4.13	23.5	14,645.4
	3	4.17	23.3	14,914.2
	4	3.83	20.8	15,344.6

pulses to pass from one transducer to the other through the material interposed between them. The model C-4901 V-meter field kit comprises the following items:

1. The V-meter.
2. Two transducers (54 kHz).
3. Two transducer leads.
4. Leather case for the V-meter.
5. Reference bar for checking zero.
6. Can of couplant
7. V-meter Manual.
8. Mains lead.

The V-Meter gives a direct reading of the time of transmission of an ultrasonic pulse passing from a transmitting to a receiving transducer. Two time ranges are incorporated covering from 0.1 micro second to 999.9 micro seconds in units of 0.1 micro second, and from 1 micro second to 9999 micro seconds in units of 1 micro second.

A simplified system diagram is shown in Figure 3-8. The construction of the V-meter can be summarized as follows:

1. The entire system is divided into four parts: (a) pulse generator, (b) set reference delay, (c) receiver amplifier, and (d) timing pulse oscillators, gate, and counter.
2. The pulse generator contains a high voltage power unit, a thyristor and UJT pulse generator. Generally, for concrete testing and for long path

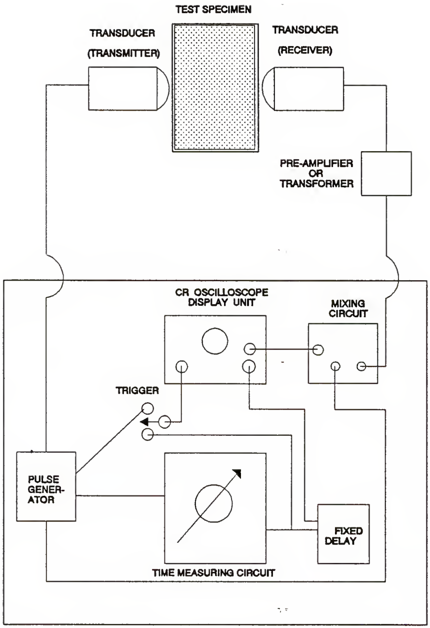

Figure 3-7: Schematic diagram of a typical apparatus of ultrasonic pulse velocity tester

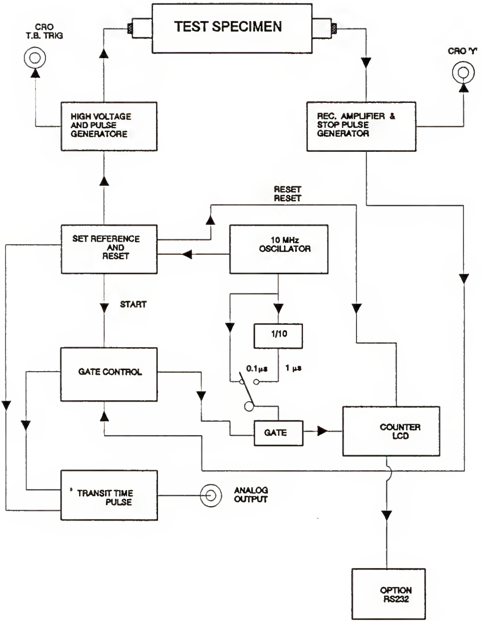

Figure 3-8: System diagram of V-meter

lengths, the generator is operated at 1,200 V. If fine cracks are being investigated, it may be advantageous to reduce the high voltage to 500 V. The capacitance of the transmitting transducers is charged to a potential of 1.2 kV or 500 V as selected by the switch on the rear panel. This capacitance is then rapidly discharged through a Thyristor triggered by the UJT at a repetition frequency of 10 or 100 pps as selected by the PRF switch. The repetition frequencies are derived from the crystal timing pulse oscillator. Discharging the capacitance causes the transmitter to be shock excited and so produce a train of longitudinal vibrations at its own natural frequency.

3. A nominal 0.5 to 10 micro second variable delay control enables the instrument to be set to a reference reading with different types of transducer and cables. This control is used in conjunction with a standard reference bar supplied with the instrument and having a transmission time of up to 25.9 micro seconds.

4. After transmission through the material under test, the ultrasonic pulse is converted to an electrical signal in the receiving transducer. The received signal is amplified and shaped to produce a steeply

rising "STOP" pulse coincident with the onset of the leading edge of the received signal waveform.

5. A 10 MHz quartz crystal oscillator module generates the timing pulses for the 0.1 micro second unit range. The 10 MHz pulses are also applied to a decade divider to produce a timing pulse at 1 MHz for the 1 micro second range.

3.2.2.3 Test locations and method

The test points are the same as locations selected in the Schmidt hammer test. The V-meter was applied on each point prior to first firing, prior to second firing, and after second firing. Thus the difference of pulse velocity at the same test point was calculated for (a) pre-firing and after first firing, and (b) after first firing and after second firing. It was then possible to evaluate the correlation between these differences and the concrete fire damage situation. It also was possible to evaluate how the three different factors (i.e., pre-exposure severity, re-curing method, and re-curing time lapse) affect the test results. By using this measuring method, the variety of variables[15] that influenced the pulse velocity can be disregarded.

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[15] The pulse velocity in concrete may be influenced by:
(a) smoothness of concrete surface under test,
(b) path length,
(c) lateral dimensions of the specimen tested,
(d) temperature of concrete,
(e) moisture condition of concrete, and
(f) presence of reinforcing steel.

There are three ways of measuring pulse velocity through concrete:

1. Direct transmission through concrete. In this method, transducers are held on opposite faces of the concrete specimen under test as shown in Figure 3-9 (A). This method is the most commonly used and is preferred to the other methods because it results in maximum sensitivity and provides a well-defined path length.
2. Semidirect transmission through concrete. Sometimes the nature of concrete surface requires that semidirect methods as shown in Figure 3-9 (B) must be used. This situation is often the case when a test path extends across a corner of a large mass of concrete.
3. Transmission along the surface. This method of pulse transmission is used when only one face of concrete surface is accessible. This method, Figure 3-9 (C), is the least satisfactory of the three methods because the maximum energy of the pulse is being directed into the concrete. Additionally, the pulse velocity measurements indicate the quality of concrete only near the surface and do not give information about deeper layers of concrete (Malhotra 1976). Thus weaker concrete that may be below a strong surface

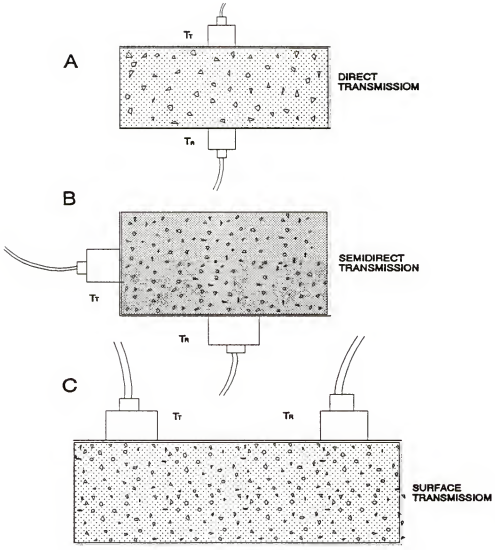

Figure 3-9: Methods of measuring pulse velocity through concrete: **A.** direct transmission method, **B.** semidirect transmission method, and **C.** surface transmission method.

concrete can go undetected. Also, in this method the path length is less well defined and it is not satisfactory to assume that it is the distance from center to center of the transducers.

The pulse velocity measuring method used in this study is the direct transmission method. The procedures of measuring at each test point can be summarized as follows:

1. Mark the exact location of each test point on both sides of concrete slab to assure that they are on the coaxial line.
2. Apply couplant on the surface of the test points and the surface of two transducers to insure there is a good acoustic coupling between the transducer face and the concrete surface in order to reach the maximum accuracy of transit time measurement.
3. Use a reference bar, with engraved pulse transit time, 25.9 μs, to check the instrument. Apply couplant to transducer faces and press the transducers firmly to both ends of the bar. Adjust the SET REF control until the reference bar transit time is obtained in the LCD.
4. Apply the transducers on the both sides of each test point and measure the transit time.

The advantage of this test method is the variation in uniformity and thickness of the specimens can be eliminated by comparison of the differences of pulse transit time at the

same test point between prior to first firing, prior to second firing, and after second firing.

3.3 Experimental Procedures

The experimental procedures of the test program can be summarized as follows (see Figure 3-10):

1. Make 27 identical concrete slabs of dimension 4 feet by 4 feet by 4 inches thick; cure all specimens for 28 days; move them into the designed drying room (142 ± 5°F, 7.5 ± 1.5% RH) until the relative humidity level within each slab is less than 75%.
2. Use ASTM E-119 test method to determine the fire endurance of 3 randomly selected specimens (control group -- Tr_{000}); use Schmidt hammer and ultrasonic V-meter to test these three specimens prior to and after firing on the same test locations.
3. Apply Schmidt hammer and ultrasonic V-meter to evaluate 12 randomly selected specimens; pre-expose these specimens in the furnace following the ASTM standard time-temperature curve for 60 minutes. After firing, randomly assign the 12 specimens into 2 different re-curing time lapse groups (30 days and 75 days). Within each group, randomly assign 6 specimens into 2 different re-curing methods group

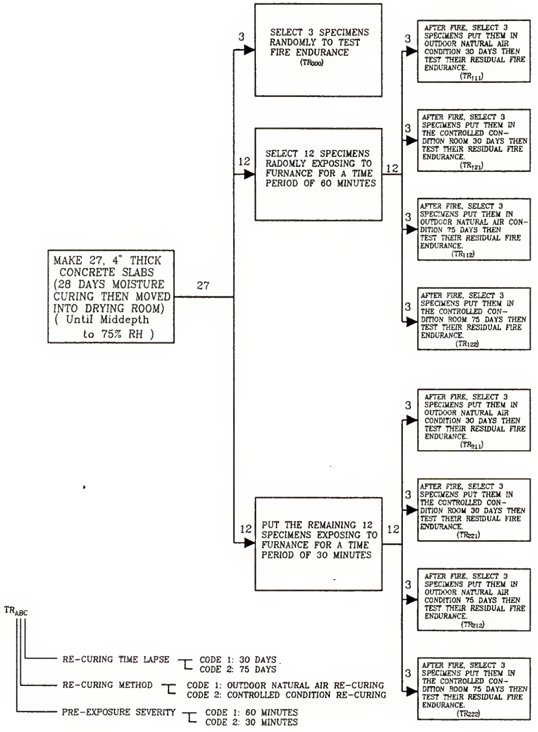

Figure 3-10: Flow chart of experimental procedures of comprehensive test program

(natural condition -- outdoor covered by plastic covering, and controlled condition -- using an air conditioned room with 45 ± 10% RH at 75 ± 10°F). After 30 days, apply Schmidt hammer and ultrasonic V-meter to test 6 specimens in 30 day-time-lapse group on the same locations on each specimen. Then following the ASTM E-119 test method to determine the residual fire endurance, Tr_{111} and Tr_{121}. After 75 days, apply Schmidt hammer and ultrasonic V-meter test to the other 6 specimens in 75 day-time-lapse group. Then, follow the ASTM E-119 test method to determine the residual fire endurance, Tr_{112} and Tr_{122}. After firing, each specimen was subjected to the Schmidt hammer and ultrasonic V-meter tests to collect the test data. The relative humidity level within each concrete specimen was recorded prior to each fire test.

4. Repeat the procedures described in step 3 but change the initial fire exposure time from 60 minutes to 30 minutes. The residual fire endurance of concrete slabs obtained in this step are Tr_{211}, Tr_{221}, Tr_{212}, and Tr_{222}.
5. All time-temperature courses on the unexposed surface of each concrete slab and within each concrete slab were recorded during each firing in the step 2 through step 4.

6. After final firing of all concrete slabs, take core samples from seven points of each specimen where the nondestructive tests were applied.
7. Finally, conduct compressive strength tests on all concrete core samples by following ASTM C-39.

CHAPTER 4
CONSTRUCTION AND CALIBRATION OF FIRE TEST FACILITIES

4.1 Organization of Test Facilities

The fire test facilities used in this research included two major parts: (1) temperature control system and (2) temperature measuring system. Figure 4-1 shows the organization and relationships of the different facilities of the entire test system.

4.2. Temperature Control System

In the research design, the pre-exposure severity and the test fire exposure applied to the specimens followed the standard time-temperature curve specified in ASTM E-119 test methods.

The purpose of the temperature control system is to insure that the same firing condition and the same time-temperature curve can be replicated during each test. When the process controller, Powers Model 512 Process Controller, of the gas burner receives a feedback signal from the type K thermocouple in the furnace by means of an electrical command signal, the controller regulates the potentiometer connected to the butterfly value that controls the rate of gas input.

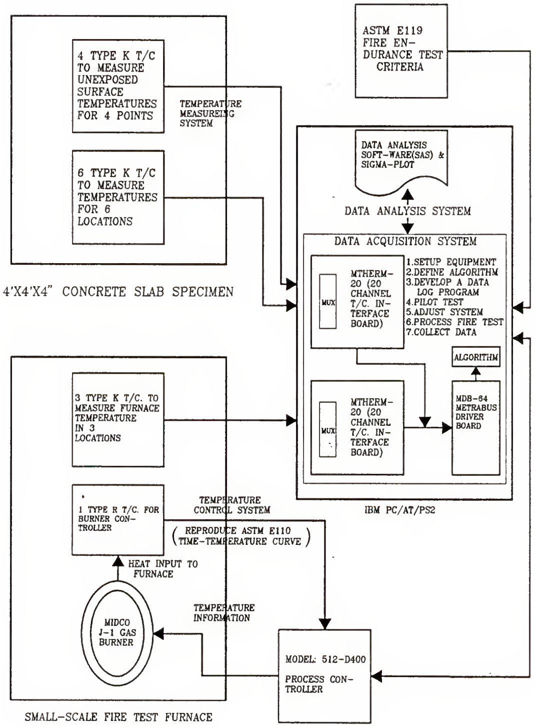

Figure 4-1: Organization of fire test facilities

If the furnace temperature is lower than the standard temperature, the controller will increase the rate of gas input; conversely, the controller will decrease the rate of gas input until the temperature follows the standard temperature.

An automatic temperature control system was designed in order that the furnace atmosphere temperature is correctly maintained during each fire test. This section describes the quality assurance plan for the design and calibration of the temperature control system.

4.2.1 Basic Equipment

4.2.1.1 Furnace body

The specifications of the small-scale fire test furnace can be summarized as follows (see Figure 4-2 and 4-3):

1. Furnace inner chamber: 40 inches by 40 inches by 40 inches.
2. Furnace body: high-temperature insulation fire brick with high-temperature ceramic fiber insulation material.
3. Structural steel exterior: the outer furnace shell is constructed of heavy angle and sheet steel.
4. Furnace opening: the furnace is open on the top to allow the operator to place the test sample in the 40 inch by 40 inch opening. The face of the opening is lined with a high-temperature resistant

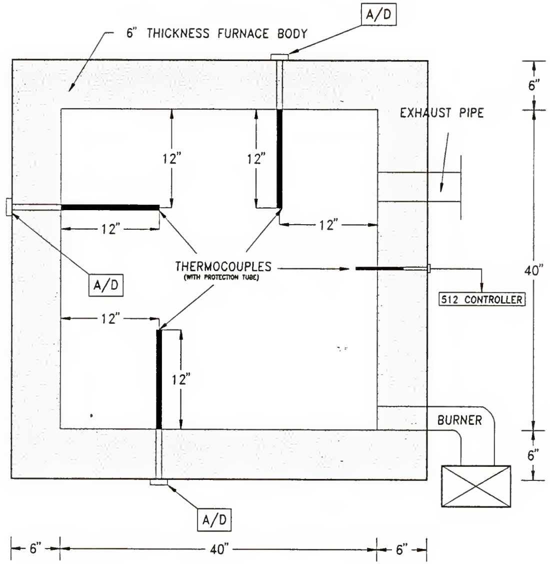

Figure 4-2: Top view of small-scale fire test furnace

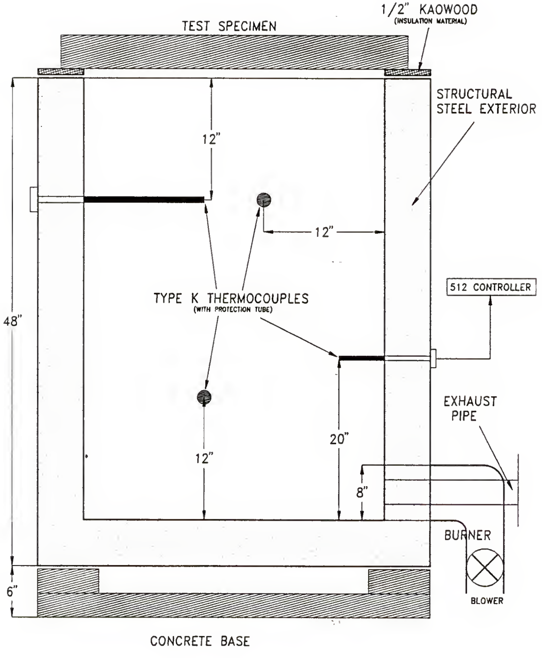

Figure 4-3: Front view of small-scale fire test furnace

fabric (i.e., Kaowood).

5. The burner inlet and the exhaust outlet are located on the bottom of one side of the furnace.

4.2.1.2 Burner

The heating equipment employed in this furnace is a model J-121-3 gas burner manufactured by MIDCO International, Inc. The specifications of this burner include

1. Capacity (BTUs Per Hour): Maximum, 1,200,000; Minimum, 50,000.
2. Gas pressure requirement: 5 inches water column.
3. Electrical supply: 120 volts, 60 Hz., 1 phase.
4. MIDCO butterfly valve.
5. Spark ignition with continuous gas pilot.
6. Honeywell RA890F electronic safety guard primary control with automatic on-off main valve.
7. Honeywell S443A manual potentiometer (0 - 135Ω).
8. Honeywell M941a modutrol motor.

4.2.1.3 Thermocouple

Three OMEGA type K thermocouples (Chromel-Alumel) were installed in the chamber of the furnace to measure furnace temperature. One OMEGA type R (Pt/Pt-13% Rh) thermocouple was used for the controller to feedback temperature measurement.

4.2.1.4 512 Process Controller

The heart of this system is the 512 Process Controller manufactured by Powers Process Controls in Chicago. The 512 Process Controller is a 1/4 DIN microprocessor-based instrument, capable of monitoring and controlling a wide variety of processes and process variables. The basic functions can be summarized as following:

1. Nine programs available: each program consists of a configurable number of ramp and/or dwell segments.
2. Ninety-nine segments available: there are up to 99 separate segments, each consisting of a starting set point setting, ending set point setting, and duration.
3. Events: during each segment, the programmer has the capability to activate or deactivate up to four different auxiliary devices.
4. Input mode: Three different input modes are available for thermocouple, RTD, and volt / milliamp.
5. Output mode: Five different output modes are available for mechanical relay, solid state relay, DC Logic, 4-20 milliamp, and position proportioning.

4.2.2 System Configuration and Control Algorithm

The process controller accomplishes system control through the following sequence:

1. attempts to accomplish temperature set point;
2. accepts the measured temperature from the feedback transducer (type R thermocouple);
3. determines the difference (called "error" or "deviation"), thereby generates an 0 - 150 Ω output signal which is related to the deviation by a preset algorithm.

This algorithm usually includes three time-dependent terms (PID), thereby providing dynamic compensation of the control loop (adjust the butterfly valve of burner). This controller is a typical analog "three-term feedback controller." The algorithm is said to be "three term" because it takes the typical form:

$$\text{Controller Output} = \frac{1}{K_p} [e + \frac{1}{T_I}\int edt + T_D \frac{de}{dt}]$$

where

$1/K_p$	=	controller steady state gain;
$100 \times K_p\%$	=	controller "proportional band;"
T_I	=	"integral action time," or "reset time;"
T_D	=	"derivative action time," or "pre-act time;" and
e	=	system error = -1 X "deviation."

The proportional term e/K_p results in a component of output proportional to error; the integral action term [$1 / (K_p \times T_I) \int edt$] results in a ramping component of output if the error is constant, and the derivative action term [$T_D/K_p \times de/dt$] results in a steady component of output if the error is ramping. This last term tends to amplify any parasitic noise components which may be present in the signal representing error, e, and therefore should be used with great caution whenever signs from the feedback transducer are noisy. This caution is because noise may exhibit high values for instantaneous rates of change even when the peak value of the noise signal may be quite small. The derivative action term [$T_D/K_p \times de/dt$] will generate an impulsive component of output if the point is changed suddenly. For this reason, some manufacturers prefer to connect the derivative action in the feedback path upstream of the error generation point. This upstream placement is done so that the set point component of the error signal can no longer be differentiated (Chesmond 1990).

If the coefficients K_p , T_I, and T_D can be adjusted independently of each other, the control law is said to be "non-interacting," and is called PID control. In many cases, not all of the terms would be used in a particle loop. For example, derivative action can be eliminated by setting T_D = 0, while integral action can be removed by setting $T_I = \infty$. Thus, it is possible to configure P, PD, PI, and PID control.

In this research design, the PI control algorithm (see Figure 4-4) was employed in the 512 control loop design in order to eliminate the error caused by noise and because it can control the fast-responding processes better than PID.

4.2.3 System Calibration

Based on the characteristics of the standard fire test furnace and the built-in functions of the process controller, the calibration processes of the temperature control system can be summarized as follows:

1. System setup: Set up the hardware and software of the control system.
2. Input and output calibration: Based on the specific type of input (thermocouple) and the controlled device, connect and calibrate the input/output apparatus.
3. Time-temperature curve segments determination: The standard time-temperature curve of ASTM E-119 was divided into 6 segments. Based on the characteristics of the standard time-temperature curve, the burner needs the most power from the first minute to the thirtieth minute; excess air then needs to be adjusted to maintain the temperature from 1,850 to 2,300°F. The set points for burner calibration include air setting and gas input setting.

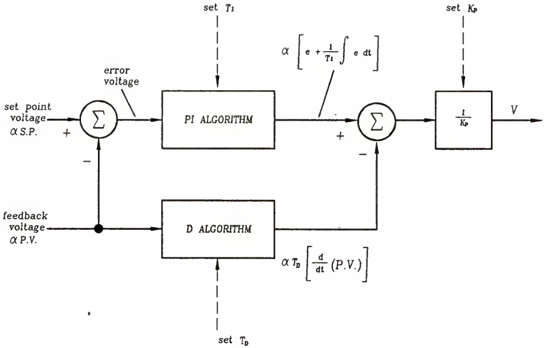

Figure 4-4: Block diagram of a feedback loop using feedback controller with PI control algorithm

4. Make a concrete sample to simulate an identical environment of test condition.
5. PID parameter tuning:
    a. select the control algorithm (in this case the PI control was selected);
    b. select the appropriate tuning algorithm to determine optimal tuning parameters;
    c. determine the configuration parameters;
    d. determine the tuning parameter (i.e., alarm set points, ratio and bias, ramp to set point, second local set point, and a pass code for panel lockout);
    e. manual output tuning (make the process approximately 5 units below the normal set point and then allow adequate time for the process to stabilize under manual output tuning);
    f. initiate self-tuning (based on the results of manual control than the output level is adjusted to keep the process variable stable at about the desire level);
    g. modify self-tuning program (to compensate for processes that are noisy or slow);
6. Develop full simulation and modeling based on automatic control;
7. Conduct fire tests.

4.3. Temperature Measuring System

4.3.1 Parameters of Measurement

The parameters that were obtained by using of this fire test equipment are

1. the temperature history of 4 points (see Figure 3-3) on the unexposed surface of each specimen;
2. the temperature history of 6 locations (see Figure 3-3) within each specimen; and
3. the fire endurance of the unburned and burned concrete slabs.

4.3.2 Digital Temperature Measuring System--Data Acquisition System

A data acquisition or computer interface system is a device that allows data from the real world to be fed into the computer (OMEGA, 1990/91). It takes the signals produced by temperature sensors, pressure transducers, or the flowmeter, and converts them into a format that is computer-compatible. With an acquisition system using a computer, it is a straightforward process to gather, monitor, display, and analyze the research data. The computer not only provides the analysis and decision-making capability but also controls the active signal-conditioning and data-conversion functions (OMEGA, 1990/91).

The primary feature of the temperature measuring system is the use of thermocouples to measure the temperature of the

test furnace and the test specimens. The results can be collected automatically by a PC-based data acquisition system, and then the process data can be analyzed. The system consists of four main components discussed below (see Figure 4-1).

4.3.2.1 Thermocouples

Fourteen OMEGA HH-K-20 (20-gauge with high-temperature glass insulation) type K (Chromel-Alumel) thermocouples for measuring the temperatures of the furnace, ambient and specimens. One OMEGA P13R-032 (0.032 inches diameter unsheathed) type R (Pt/Pt-13% Rh) thermocouple feeds the temperature readings to the process controller to control the J-121-3 gas burner.

4.3.2.2 MTHERM-20

The MTHERM-20 is a thermocouple input board providing 20 differential input channels. For the design of a data acquisition and control system, the MTHERM-20 employs a 12-bit integrating A/D converter and 20-channel multiplexer (MUX). The MTHERM-20 system is compatible with a broad range of personal computers and bus structures including IBM PC/XT/AT and compatibles, VMEbus, MicroVAX II, and virtually all other large or small computers supporting data input/output via the serial input port (RS-232/422/485). The seven industry standard thermocouples (type J, K, T, R, S, B, or E) are

supported directly with data conversion to Fahrenheit or Centigrade. The cold junction compensation circuit can be disabled for direct measurement of millivolts in any of four different full-scale input ranges (0 to 76.4 mV, 0 to 25 mV, 0 to 15 mV or 0 to 5 mV) (KEITHLEY 1990).

4.3.2.3 MDB-64

MDB-64 is the METRABUS driver board which can interface the METRABUS system to the IBM PC/XT/AT or compatible. It allows a single PC expansion slot to control up to 64 external METRABUS input/output boards. This capability means that a single MDB-64 can interface to 512 digital or 256 analog input/output points. Also, the METRABUS system is easily programmed via the timing and control signals generated by the MDB-64 (KEITHLEY 1990).

4.3.2.4 DTK 286 PC/AT computer

The Tech-1230C personal computer made by Datatech Enterprises Company consists of a 16 mHz Mini286 mainboard (PC/AT compatible), 1MB RAM, power supply unit, one 3.25" floppy disk drive, 40MB hard disk drive, and TTX-CVG-5432/39 VGA monitor.

4.3.3 Calibration of Temperature Measuring System

The accuracy of the thermocouples employed in research should be determined carefully before calibration. In order

to obtain the high accuracy usually associated with calibration at fixed points, it is necessary to follow certain procedures with special precautions. This section describes the field calibration of temperature measurement of the entire system and the system error estimation of the system employing thermocouple and thermocouple interface board.

4.3.3.1 Field calibration of thermocouple and interface board

The thermocouple interface board, MTHERM-20, provides an on-board cold junction compensation circuit and a microprocessor that can compute the temperature from the measured input voltage, apply cold junction compensation, and store the results (with internal 256 bytes of RAM) until retrieved. The interface board allows a practical method for Type K and Type R thermocouple calibration which can be carried out on the job site before the entire system is installed. For time saving, the calibration was based on the lump sum reading which comes from the results of the thermocouple connected to the interface board. One type T thermocouple calibrated by National Bureau of Standard (NBS)[1] and one Hewlett Packard Model 3490A multimeter were used to calibrate the temperature measuring system. The calibration process can be summarized as follows:

---

[1] The calibration was conducted by James F. Schooley, chief of Temperature Measurements and Standards Division in NBS on November 17, 1980, for the Department of Mechanical Engineering at University of Florida (Report number: 224096).

1. Select four type K thermocouples randomly from all thermocouples used in this research.[2]
2. Prepare one isothermal chamber.
3. Connect four thermocouples with the MTHERM-20 interface board.
4. Connect the type T calibrated (standard) thermocouple to HP 3490A multimeter; then select an appropriate output range of voltage.
5. Place the all five thermocouples into the isothermal chamber at least 1 minute before reading the output voltages.
6. Activate the data acquisition system and record the temperature reading as well as the microvoltage output of the HP 3490A multimeter (see Figure 4-5).
7. Change the temperature in the isothermal chamber and repeat Step 5. Table 4-1 shows the calibration results.
8. Take average temperature of four type K thermocouples versus the temperature of type T thermocouple using curve fitting equation to obtain

[2] Because of the possibility of noise from the impedance of the thermocouple, the length of the thermocouple applied to calibration should be as long as the length of thermocouples used in the data acquisition system.

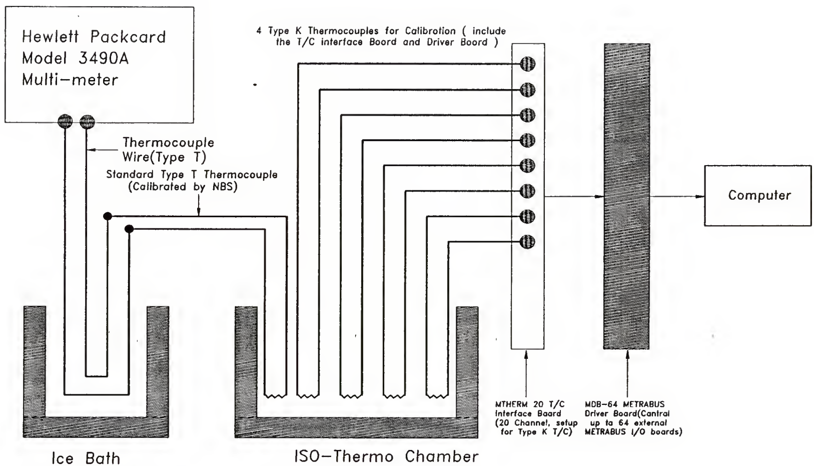

Figure 4-5 Type K thermocouple calibration diagram

Table 4-1: Data summary of thermocouple calibration

Type T Thermocouple		Type K T/C No. 1 (°F)	Type K T/C No. 2 (°F)	Type K T/C No. 3 (°F)	Type K T/C No. 4 (°F)	Average Temp. of Type K T/C
Micro-voltage	Temperature (°F)					
3480.00	181.04	173.10	173.10	173.10	172.30	172.90
2997.00	161.76	166.10	156.10	156.10	156.10	158.60
2681.00	148.91	143.20	1[illegible]2.[illegible]0	143.20	142.8	142.93
2336.00	143.73	129.70	1[illegible]2.80	129.70	129.70	129.33
1983.00	116.90	116.90	116.90	116.90	116.90	116.40
1597.00	103.48	102.30	102.00	102.30	101.60	102.05
1349.00	92.77	92.10	91.30	92.10	91.20	91.68
86.00	36.01	36.01	34.50	35.50	34.30	35.10
472.00	53.74	52.30	49.90	50.80	50.50	50.88
3219.00	170.67	164.20	163.00	163.50	133.00	163.43
3400.00	178.07	170.07	169.50	169.80	169.60	169.85
2835.00	155.21	149.10	143.20	149.10	148.20	148.65
2484.00	142.65	134.20	116.90	134.70	133.80	134.13
1776.00	111.15	108.10	107.90	108.30	107.50	107.95
533.00	56.52	58.80	57.90	58.80	58.80	58.58
4046.00	'203.27	197.20	197.20	197.40	197.00	197.20
3508.00	182.17	174.70	173.80	174.70	174.30	174.38
3720.00	190.56	183.10	183.10	183.70	183.10	183.25
3156.00	168.15	162.30	161.90	162.40	162.40	162.25
1153.00	84.20	82.30	81.40	82.30	82.30	82.08
893.00	72.7	70.50	69.90	70.80	70.80	70.50
709.00	64.40	62.50	62.20	62.70	62.50	62.48
259.00	44.01	42.90	42.90	43.50	43.30	43.15

the calibration coefficients.[3]

9. Modify the data acquisition computer software based upon the calibration coefficients.

4.3.3.2 Estimation of system error

The system error in measuring temperature with MTHERM-20 can be stated as being composed of the following components (Keithley 1990):

$$E = A + B + C + D$$

where

A = thermocouple sensor error, 3.96°F or 0.75% (above 32°F); 3.96°F or 2.0% (below 32°F), whichever is greater.

B = signal conditioning, A/D, and computational errors. This value is twice the resolution or at best 0.72°F (type K).

If the local cold junction compensation (CJC) is used to correct measurement, then:

C = CJC measurement, 0.9 °F (0 to 90 °F).

---

[3] Fitted polynomial equation:

$$Y = a(1) + a(2)\ X + a(3)\ X^2 + \ldots + a(m+1)\ x^m$$

where m is order. The three coefficients, a(j), for 2nd-order polynomial are a(1)= -.16586186E+01, a(2)= .10485202E+01, and a(3)= .70284439E-05

D = channel-to-channel temperature gradient at the terminal strip. At 77°F, in still air situations, this has been measured to be about ± 1.26°F from channel 1 to 20. With proper forced air ventilation, this can be lowered to ± 0.18°F.

E = the error of the entire temperature measuring system with MTHERM-20.

Under normal conditions (temperature measurement range above 32°F, using MTHERM-20 board, with CJC measurement, and 77°F still air situation), the probable system error (or system accuracy) of this data acquisition system will be close to 6.84°F (about 0.15 mV for Type K thermocouple) based upon the 12-bit, "Dual-Slope Integrating" A/D converter.

4.3.4 Temperature Offset Tolerance of Furnace

According to the requirements stated in section 4 of the ASTM E-119, the accuracy of the furnace control shall be such that the area under the time-temperature curve, obtained by averaging[4] the results from the thermocouple readings, is within 10% of the corresponding area under the standard time-temperature curve for a fire test of 1 hour or less duration. The accuracy is within 7.5% for those over 1 hour and not more than 2 hours, and 5% for tests exceeding 2 hours in duration. A formula in ASTM E-119 Standard Test Method allows for the

[4] Normally, the high-frequency noise in the system can be eliminated by averaging the parameter(s) measured in this system.

correction of the test results for minor flaws in the temperature-time curve of the furnace. This correction formula is

$$\Delta\tau = \tau\ (\frac{2}{3})\ \frac{(A - A_s)}{(A_s + L)}$$

where

$\Delta\tau$ = fire resistance credit (or debit, if $A < A_s$), min,

τ = measured fire resistance time (time of successful endurance of a test fire), min,

A = area under actual furnace temperature-versus-time curve for first three-quarters of τ, °F min,

A_s = area under standard furnace-temperature-versus-time curve for first three quarters of τ, °F min, and,

L = area associated with thermal lag of furnace thermocuples during initial period of test (= 3240°F-min).

This formula can be rewritten in the form

$$\frac{\Delta\tau}{\Delta A} = \frac{2}{3}\ \frac{\tau}{(A_s + L)}$$

where

ΔA = $(A - A_s)$, °F-min. Clearly, the right side of the equation is a function of τ only.

Harmathy (1985) criticized the empirical formula given in the ASTM E-119 standard because it might yield low corrections. It is quite difficult, however, to devise a simple formula for correcting the fire test result even according to his "normalized heat load"[5] theory because of flaws in the furnace temperature. Thus, in this study the traditional correction formula was used to correct the test result of a non-standard time-temperature test situations. This adjustment, based on the "equivalent fire exposure" concept (Harmathy 1987), is the last opportunity to compensate the temperature offset during the fire tests.

4.3.5 Sampling Frequency and Aliasing of System

During the study, sampling and data conversions are key steps to getting the necessary measurement information. When

[5] The concept of normalized heat load has been developed for several years by Dr. T. Z. Harmathy. It is defined as

$$H = \frac{1}{\sqrt{k\mu c}} \int_0^\tau q\,dt$$

where

$\sqrt{k\mu c}$	=	thermal inertia of the boundaries of the compartment
k	=	thermal conductivity
μ	=	density
c	=	specific heat
q	=	heat flux penetrating the compartment boundaries
t	=	time
τ	=	duration of fire

continuous analog signals are obtained in a measurement process, they are frequently somewhat analogous. Processing them is not the main objective. The real objective is to obtain the information which can be extracted from them and/or to use this information for control purposes or measuring. Normally, there are two choices for handling the analog signal: (1) process the analog signal directly to achieve a desired control function using an analog control system, or (2) convert the information to another more useful form.

Sampling is a procedure for creating a set of point values which describe a waveform but do not preserve the whole continuous waveform (Doddington 1986). If such a process can preserve the complete information content of the waveform, there are obviously important implications concerning efficient transmission and storage of information from the signals. The major problem is to determine how all the information from an infinite signal bandwidth, which represents a physical variable, can be preserved by a finite, discrete set of point values taken from the original signal using some simple set of rules so that the original information signal can be reconstructed (Doddington, 1986).

For example, aliasing is a key factor in the sampling rate. The aliasing phenomenon makes a helicopter's rotor blades appear to be moving slowly backwards in a movie. In data acquisition systems the same process can occur; analog

input can show a slowly moving input signal that is actually a very-high-frequency phenomenon.

For instance, analog signals are continuous functions over time. Time quantitization is used to transmit such signals in a pulsed format, whereby the signal is defined or measured at only discrete time intervals. If the sampling rate is sufficiently high, information should not be lost by this technique (Sinnema & McGovern 1986). Based on "sampling theory"[6] to sample a continuous time signal x(t) is to represent x(t) at a discrete number of points, t = nT, where T is the sampling period and n is an integer that establishes the time position of each sample. The minimum sampling frequency is $2f_h$ Hertz, where f_h is the highest frequency in x(t) (Ziemer, Tranter, & Fannin 1989). If the signal is sampled below the Nyquist rate,

$$f_s - f_h \leq f_h$$

the lower sideband at f_s will overlap with the baseband and distortion will occur. This effect is termed aliasing, or frequency foldover distortion. On the other hand, if there is little or no input signal above the sample rate, then aliasing is usually not a significant problem.

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[6] A band limited signal x(t), having no frequency components above f_z Hertz, is completely specified samples that are taken at a uniform rate greater than $2f_z$ Hertz. In other words, the time between samples is no greater than $1/2f_z$ seconds. The frequency $2f_z$ is known as the Nyquist rate.

When using ASTM E-119 standard, the test furnace is a typical thermal system. A heat conduction equation is a parabolic equation which is not a waveform (nonperiodic) physical quantity and having no finite speed. In other words, the furnace system is a low-frequency energy system which has very small bandwidth and a large time constant. Also, the thermocouple output signal based on this system is a non-waveform analog signal. Additionally, because this thermal system is similar to an overdamped (its damping ratio is greater than 1) wave system, it is an exponentially decaying form and the input energy is time varying based on the ASTM E-119 time-temperature curve. Thus, aliasing will not be a problem in this data acquisition system. For sake of conservation, however, the sampling frequency in the data acquisition system was set to the ultimate capacity of hardware.[7]

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[7] 1.25 seconds for 20 channel inputs.

CHAPTER 5
METHOD OF DATA ANALYSIS

5.1 Introduction

This laboratory test program explores the feasibility and reliability of using small-scale specimens for evaluating both the residual fire endurance of burned concrete slabs and the extent of fire damage, and to investigate the possible cause-and-effect relationships of three different factors (i.e., pre-exposure fire severity, re-curing method, and re-curing time lapse) and the properties of the burned concrete element (i.e., the residual fire endurance, the seven-point average percentage loss of rebound number, and the seven-point average percentage loss of pulse velocity).

Evaluation of the significance of the effects of these various factors on the properties of the burned concrete slabs is done by using the analysis of variance (ANOVA) statistical method. Since the experimental design is a typical fixed-effects 2 X 2 X 2 full factorial design, the data can be analyzed by the ANOVA model, which incorporates all factors and interactions studied.

Based on the sample size estimation program available with the SAS Program (see Table 5-1) and the "Tables of Sample Sizes in the Analysis of Variance" by Bratcher, Moran and

Table 5-1: SAS program for estimation of sample size of three-factor fixed effects design

```
************   SAS PROGRAM FOR SAMPLE SIZE ESTIMATION   ************** ;
* This program computes sample sizes for a three-factor fixed effects, ;
* equally replicated, fully factorial design for a given ALPHA, BETA,  ;
* and LAMBDAP (α1=-1.5, α2=+1.5) for marginal effects of factor has a  ;
* power of at least 0.9 when the significance level is 0.05           ;
OPTIONS LS=70;
DATA POWER;
 ALPHA=.05;
 POWER=.90;
 LAMBDAP=4.5;
 A=2;
 B=2;
 C=2;
 DF1=A-1;
 n=1;
 APOWER=0;
 CV=10.0;
 DO WHILE (APOWER < POWER);
   n=n+1;
   DF2= A*B*C*(n-1);
   LAMBDAA= B*C*n*LAMBDAP;
   P = 1.0 - PROBF(CV,DF1,DF2);
   DO UNTIL (P>ALPHA);
     CV=CV-0:001;
     P = 1 - PROBF(CV, DF1, DF2);
   END;
   CV=CV+0.001;
   APOWER = 1.0 - PROBF (CV, DF1, DF2, LAMBDAA);
 END;
PROC PRINT;
VAR LAMBDAA ALPHA POWER CV n APOWER;
RUN;
```

Zimmer (1970), in the given power $(1 - \beta) = 0.9$, $\Delta/\sigma = 3.0$, and $\alpha = 0.05$, $r = 2$, the optimum sample size for each observation cell is 3.[1]

The data structure of results can be summarized in Table 5-2. The same data structure was used in the nondestructive test results except where the residual fire endurance of each specimen was replaced by: (a) the seven-point average percentage loss of rebound number of each specimen and (b) the seven-point average percentage loss of pulse velocity of each specimen.

5.2 Model of Analysis of Variance

The three-factor analysis of variance model for this experimental design can be described by the following linear models.

1. Three-way linear model for the fire endurance of pre-burned concrete slabs:

$$Tr_{ijkl} = \mu + S_i + M_j + T_k + (SM)_{ij} + (ST)_{ik} + (MT)_{jk} + (SMT)_{ijk} + \epsilon_{ijkl}$$

$$i = j = k = 1, 2; \quad l = 1, 2, 3$$

where

---

[1] Where α = the probability of type I error,
β = the probability of type II error,
Δ = the range between largest and smallest treatment means, and
r = number of treatments.

Table 5-2: Data structure of test results (fire test)

Pre-exposure Fire Severity	Re-curing Time Lapse			
	30 Days		75 Days	
	Natural Environment Re-curing	Conditioning Room Re-curing	Natural Environment Re-curing	Conditioning Room Re-curing
60 Minutes	Tr_{111}-A Tr_{111}-B Tr_{111}-C	Tr_{121}-A Tr_{121}-B Tr_{121}-C	Tr_{112}-A Tr_{112}-B Tr_{112}-C	Tr_{122}-A Tr_{122}-B Tr_{122}-C
30 Minutes	Tr_{211}-A Tr_{211}-B Tr_{211}-C	Tr_{221}-A Tr_{221}-B Tr_{221}-C	Tr_{212}-A Tr_{212}-B Tr_{212}-C	Tr_{222}-A Tr_{222}-B Tr_{222}-C

Tr_{ijkl} = the residual fire endurance of the l^{th} specimen of k^{th} re-curing method, j^{th} re-curing time lapse, i^{th} pre-exposure fire severity;

μ = overall mean of residual fire endurance;

S_i = effect of i^{th} pre-exposure fire severity;

M_j = effect of j^{th} re-curing method;

T_k = effect of k^{th} re-curing time lapse;

$(SM)_{ij}$ = effect of the interaction of the i^{th} pre-exposure fire severity and the j^{th} re-curing method;

$(ST)_{ik}$ = effect of the interaction of the i^{th} pre-exposure fire severity and the k^{th} re-curing time lapse;

$(MT)_{jk}$ = effect of the interaction of the j^{th} re-curing method and the k^{th} re-curing time lapse;

$(SMT)_{ijk}$ = effect of the interaction of the i^{th} pre-exposure fire severity and the j^{th} re-curing method and the k^{th} re-curing time lapse; and

ϵ_{ijkl} = random error.

2. Three-way linear model for the seven-point average percentage loss[2] of rebound number of concrete slabs due to fire damage:

---

[2] The percentage loss of rebound number between first measurement and second measurement on each test point.

$$Rr_{ijkl} = \mu + S_i + M_j + T_k + (SM)_{ij} + (ST)_{ik} + (MT)_{jk} + (SMT)_{ijk} + \epsilon_{ijkl}$$

$$i = j = k = 1, 2; \quad l = 1, 2, 3$$

where

Rr_{ijkl} = the seven-point average percentage loss of rebound number of the l^{th} specimen of k^{th} re-curing method, j^{th} re-curing time lapse, i^{th} pre-exposure fire severity;

μ = overall mean of the seven-point average percentage loss of rebound number;

S_i = effect of i^{th} pre-exposure fire severity;

M_j = effect of j^{th} re-curing method;

T_k = effect of k^{th} re-curing time lapse;

$(SM)_{ij}$ = effect of the interaction of the i^{th} pre-exposure fire severity and the j^{th} re-curing method;

$(ST)_{ik}$ = effect of the interaction of the i^{th} pre-exposure fire severity and the k^{th} re-curing time lapse;

$(MT)_{jk}$ = effect of the interaction of the j^{th} re-curing method and the k^{th} re-curing time lapse;

$(SMT)_{ijk}$ = effect of the interaction of the i^{th} pre-exposure fire severity and the j^{th} re-curing method and the k^{th} re-curing time lapse; and

ϵ_{ijkl} = random error.

3. Three-way linear model for the seven-point average percentage loss[3] of pulse velocity of concrete slabs due to fire damage:

$$Vr_{ijkl} = \mu + S_i + M_j + T_k + (SM)_{ij} + (ST)_{ik} + (MT)_{jk} + (SMT)_{ijk} + \epsilon_{ijkl}$$

$$i = j = k = 1,\ 2; \quad l = 1,\ 2,\ 3$$

where

Vr_{ijkl} = the seven-point average percentage loss of pulse velocity of the l^{th} specimen of k^{th} re-curing method, j^{th} re-curing time lapse, i^{th} pre-exposure fire severity;

μ = overall mean of the seven-point average percentage loss of pulse velocity;

S_i = effect of i^{th} pre-exposure fire severity;

M_j = effect of j^{th} re-curing method;

T_k = effect of k^{th} re-curing time lapse;

$(SM)_{ij}$ = effect of the interaction of the i^{th} pre-exposure fire severity and the j^{th} re-curing method;

$(ST)_{ik}$ = effect of the interaction of the i^{th} pre-exposure fire severity and the k^{th} re-curing time lapse;

$(MT)_{jk}$ = effect of the interaction of the j^{th} re-curing method and the k^{th} re-curing time lapse;

---

[3] The percentage loss of pulse velocity between first measurement and second measurement.

$(SMT)_{ijk}$ = effect of the interaction of the i^{th} pre-exposure fire severity and the j^{th} re-curing method and the k^{th} re-curing time lapse; and

ϵ_{ijkl} = random error.

A multiple comparison was conducted to compare the means of residual fire endurance at two different pre-exposure fire severity levels to the mean of fire endurance of the control group which did not receive the treatments.

5.3 Statistical Hypothesis

5.3.1 Research Hypotheses for the Fire Endurance Test

This research involves testing of the following hypotheses on residual fire resistance test results:

H_1: There are significant interactions among different 3-factor combination effects (pre-exposure severity * re-curing method * re-curing time lapse).

H_2: There are significant interactions among different 2-factor combination effects (pre-exposure severity * re-curing method).

H_3: There are significant interactions among different 2-factor combination effects (pre-exposure severity * re-curing time lapse).

H_4: There are significant interactions among different 2-factor combination effects (re-curing method * re-curing time lapse).

H_5: There is a significant difference in fire endurance of burned concrete slabs between the two levels of pre-exposure severity.

H_6: There is a significant difference in fire endurance of burned concrete slabs between the two levels of re-curing method.

H_7: There is a significant difference in fire endurance of burned concrete slabs between the two levels of re-curing time lapse.

H_8: There is a significant difference in fire endurance of burned concrete slabs between two experimental groups and control group.

5.3.2 Research Hypotheses for the Schmidt Rebound Hammer Test

This research involves testing of the following hypotheses on Schmidt rebound hammer test results:

H_1: There are significant interactions among different 3-factor combination effects (pre-exposure severity * re-curing method * re-curing time lapse).

H_2: There are significant interactions among different 2-factor combination effects (pre-exposure severity * re-curing method).

H_3: There are significant interactions among different 2-factor combination effects (pre-exposure severity * re-curing time lapse).

H_4: There are significant interactions among different 2-factor combination effects (re-curing method * re-curing time lapse).

H_5: There is a significant difference in the seven-point average percentage loss of rebound numbers between the two levels of pre-exposure severity.

H_6: There is a significant difference in the seven point average percentage loss of rebound numbers between the two levels of re-curing method.

H_7: There is a significant difference in the seven-point average percentage loss of rebound numbers between the two levels of re-curing time lapse.

5.3.3 Research Hypotheses for the Ultrasonic Pulse Velocity Test

This research involves testing of the following hypotheses on the ultrasonic pulse velocity test results:

H_1: There are significant interactions among different 3-factor combination effects (pre-exposure severity * re-curing method * re-curing time lapse).

H_2: There are significant interactions among different 2-factor combination effects (pre-exposure severity * re-curing method).

H_3: There are significant interactions among different 2-factor combination effects (pre-exposure severity * re-curing time lapse).

H_4: There are significant interactions among different 2-factor combination effects (re-curing method * re-curing time lapse).

H_5: There is a significant difference in the seven-point average percentage loss of pulse velocities between the two levels of pre-exposure severity.

H_6: There is a significant difference in the seven-point average percentage loss of pulse velocities between the two levels of re-curing method.

H_7: There is a significant difference in the seven point average percentage loss of pulse velocities between the two levels of re-curing time lapse.

CHAPTER 6
TEST RESULTS

6.1 Results of Fire Endurance Test

6.1.1 Summary of Test Results

Table A in Appendix A shows the detailed fire endurance test results of the 27 (one missing data)[1] regular and pre-burned concrete slabs. The results are summarized in Table 6-1.

By following the requirements specified in ASTM E-119 standard, the fire endurance of each specimen was adjusted, first, for the furnace temperatures during each fire test, and then, for the moisture content of each specimen. Table 6-2 shows the computer program used to adjust the fire endurance for the nonstandard furnace temperature. Because the concrete specimen contained more than 6% Portland cement by volume, correction for the fire endurance of the nonstandard moisture content was necessary. This second adjustment was applied to each specimen after adjustment for the nonstandard furnace temperature. Table B in Appendix B shows the corrected data.

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[1] Specimen No. Tr_{221}-A broke into parts after first firing when being removed from the furnace.

Table 6-1: Summary data of fire endurance test results on regular and burned concrete slabs

Number of Specimen	Fire Endurance of Regular and Burned Concrete Slabs (minutes)		Adjusted Fire Endurance (for different Moisture Content) (minute)	Remark of Specimen
	Test Condition	Standard Condition		
Tr_{000}-A	90.23	87.23	102.0	Control Group
Tr_{000}-B	90.96	98.72	102.0	
Tr_{000}-C	95.10	90.96	109.2	
Tr_{111}-A	79.77	77.23	78.8	Experimental Group
Tr_{111}-B	78.17	77.23	78.0	
Tr_{111}-C	76.80	83.13	85.2	
Tr_{121}-A	76.93	75.08	95.1	Experimental Group
Tr_{121}-B	90.23	70.33	73.8	
Tr_{121}-C	76.33	75.33	78.0	
Tr_{112}-A	76.80	76.93	77.4	Experimental Group
Tr_{112}-B	74.5	73.12	73.5	
Tr_{112}-C	82.97	82.78	85.2	
Tr_{122}-A	82.7	61.7	65.4	Experimental Group
Tr_{122}-B	77.17	77.24	81.0	
Tr_{122}-C	75.77	75.08	78.6	
Tr_{211}-A	76.80	74.51	73.8	Experimental Group
Tr_{211}-B	99.67	98.72	95.1	
Tr_{211}_C	90.23	77.89	78.3	
Tr_{221}-B	68.5	66.99	68.4	Experimental Group
Tr_{221}-C	85.39	66.96	78.0	
Tr_{212}-A	87.13	85.39	82.8	Experimental Group
Tr_{212}-B	82.7	81.55	82.8	
Tr_{212}_C	81.9	80.73	79.8	
Tr_{222}-A	84.85	84.7	85.8	Experimental Group
Tr_{222}-B	79.17	77.77	81.0	
Tr_{222}_C	85.17	84.66	89.1	

Note: The burned concrete specimens were subjected to either 60 minutes or 30 minutes pre-exposure severity treatment.

Table 6-2: Computer program for correcting fire endurance under nonstandard furnace temperature

```
%load x22.dat ;
%x1=x22;
L = 3240 ;
N=length(x1)
period = length(x1)-1 ;
t=[0.0:0.5:0.5*period];
temp=68+517.5*log10(23.7634*t+1);
%plot(t,x1,t,temp);
%pause
interval = ceil(3*period/4) ;
A1= 0 ;
A2 = 0 ;
for i=1:interval
    A1= x1(i)+x1(i+1)+A1 ;
    A2 = temp(i)+temp(i+1)+A2 ;
end
A = 0.5*0.5*A1;
As = 0.5*0.5*A2 ;
c1 = 0.5*period*(A-As)/(As+L) ;
c = 2*c1/3 ;
disp('experiment valule')
0.5*period
disp('correction value')
c
disp('true value')
c+0.5*period
```

The test results also are presented in a different form in Table 6-3. Temperature measurements on the unexposed surface of concrete slabs are listed in Appendix C.

6.1.2 Analysis of Test Results

The overall mean of residual fire endurance of the 23 burned concrete slabs[2] is 79.122 minutes with a standard deviation of 6.125 minutes. The averages of fire endurance measurements in each observation cell are summarized in Table 6-4.

Analysis of variance (ANOVA) was performed on the test results by using the model as shown in Chapter 5. Results of the ANOVA are summarized in Table 6-5. From Table 6-5, all p values are greater than 0.05, which indicates that all the main effects (i.e., S, M, and T) and interactions (i.e., S*M, S*T, M*T, and S*M*T) are not significant at an α level of 0.05. In other words, the treatments applied to the concrete slabs did not produce significantly different affects on the residual fire endurance of concrete slabs. Because there are only two levels of each main effect and no main effect produce significantly different results based on ANOVA, no further comparison test was performed.

Since there is a missing concrete specimen, the appropriate general linear models (GLM) procedure for ANOVA

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[2] The concrete specimens subjected to either 60 minutes or 30 minutes pre-exposure severity treatment.

Table 6-3: Data summary of fire endurance test results based on the three factor fixed-effect design

Pre-exposure Fire Severity	Re-curing Time Lapse			
	30 Days		75 Days	
	Natural Environment Re-curing	Conditioning Room Re-curing	Natural Environment Re-curing	Conditioning Room Re-curing
60 Minutes	76.8 78.0 85.2	78.6 73.8 78.0	77.4 73.5 85.2	65.4 81.0 78.6
30 Minutes	73.8 95.1 78.3	*** 68.4 71.4	82.8 82.8 79.8	85.8 81.0 89.0

*** Missing Specimen

Table 6-4: Average fire endurance of each observation cell

Observation Cell	Number of Experimental Unit	Mean of Residual Fire Endurance (minute)	Standard Deviation (minute)
Tr_{111}	3	80.0	4.543
Tr_{121}	3	76.8	2.615
Tr_{112}	3	76.8	5.957
Tr_{122}	3	75.0	2.615
Tr_{211}	3	80.0	11.226
Tr_{221}	2	69.9	2.121
Tr_{212}	3	81.8	1.732
Tr_{222}	3	85.3	4.073

Table 6-5: Results of ANOVA on fire endurance test data under 2 X 2 X 2 factorial design model

Factor	DF	ANOVA SS	F Value	P Value
S	1	56.21	1.50	0.2398
M	1	64.49	1.72	0.2095
T	1	29.17	0.78	0.3918
S*M	1	0.00	0.00	1.0000
S*T	1	81.19	2.16	0.1620
M*T	1	75.35	2.01	0.1769
S*M*T	1	106.82	2.85	0.1122
Error	15	562.8		

suggested by SAS software was performed. Table 6-6 shows the ANOVA results from GLM procedure where it can be seen that there was no significant difference among main effects or interactions. The conclusion drawn from Table 6-5 was therefore not altered.

6.1.3 Comparison of Test Results

The experimental treatments did not display a significant difference in residual fire endurance between the different treatment groups. However, it was of interest to evaluate how much fire resistive ability of burned concrete slabs remained after exposure to the two different levels of fire severity.

The residual fire endurance of test specimens under the two levels of pre-exposure severity treatment, 60 minutes and 30 minutes, and the fire endurance of test specimens in the control group, which did not receive the treatment, were re-organized as a three-treatment, one-way classification design. Table 6-7 shows the data structure. The mean residual fire endurance of the specimens subjected to 60 minutes of pre-exposure severity is 77.63 minutes with a standard deviation of 5.31 minutes; the mean residual fire endurance of the specimens subjected to 30 minutes of pre-exposure severity is 80.76 minutes with a standard deviation of 7.78 minutes; and the mean fire endurance of the specimens in the control group is 104.4 minutes with a standard deviation of 4.16 minutes.

Analysis of variance was performed on this one-way

Table 6-6: Results of ANOVA on fire endurance test data under 2 X 2 X 2 factorial design model by using GLM procedure

Factor	df	Type III SS	F value	P
S	1	27.96	0.75	0.4016
M	1	89.23	2.38	0.1439
T	1	48.31	1.29	0.2743
S*M	1	1.56	0.04	0.8413
S*T	1	113.09	3.01	0.1030
M*T	1	84.79	2.26	0.1535
S*M*T	1	96.09	2.56	0.1304
Error	15	562.8		

Table 6-7: Fire endurance of concrete specimen under different pre-exposed severity treatment

Treatment 1 *		Treatment 2 **		Treatment 3 ***	
No. of Specimen	Fire Endurance (minute)	No. of Specimen	Fire Endurance (minute)	No. of Specimen	Fire Endurance (minute)
Tr_{111}-A	76.8	Tr_{211}-A	73.8	Tr_{000}-A	102.0
Tr_{111}-B	78.0	Tr_{211}-B	78.3	Tr_{000}-B	102.0
Tr_{111}-C	85.2	Tr_{211}-C	78.3	Tr_{000}-C	109.2
Tr_{121}-A	82.8	Tr_{221}-C	68.4		
Tr_{121}-B	73.8	Tr_{221}-C	71.4		
Tr_{121}-B	82.0	Tr_{212}-B	82.8		
Tr_{112}-B	77.4	Tr_{212}-B	82.8		
Tr_{112}-B	73.8	Tr_{212}-C	79.8		
Tr_{112}-B	85.2	Tr_{222}-A	85.8		
Tr_{122}-A	65.4	Tr_{222}-C	81.0		
Tr_{122}-B	81.0	Tr_{222}-C	89.1		
Tr_{122}-C	78.6				
Mean	77.626	Mean	80.755	Mean	104.4

* The concrete specimens subjected to 60 minutes pre-exposure treatment prior to the fire endurance test.

** The concrete specimens subjected to 30 minutes pre-exposure treatment prior to the fire endurance test.

*** The concrete specimens did not subject to pre-exposure treatment prior to fire endurance test.

classification model with the data in Table 6-7. Results of ANOVA are summarized in Table 6-8. Table 6-8 shows that a significant difference existed among the treatments.

Four multiple-comparison procedures were conducted following the analysis of variance. The Student-Newman-Keuls test at the 0.05 level of significance was used to compare the means of fire endurance (see Table 6-9). It can be seen that the fire endurance of the control group is significantly higher than the fire endurance of the two experimental groups that were subjected to 60 minutes and 30 minutes pre-exposure treatment, respectively. No significant difference was detected between the 60-minute group and 30-minute group. This finding is in agreement with the conclusion reached from the results of the ANOVA of 2 X 2 X 2 factorial design. The same conclusion can be drawn from the other multiple-comparison procedures: Duncan's Multiple Range test (see Table 6-10), Tukey's Studentized Range (HSD) test (see Table 6-11), and Scheffe's test (see Table 6-12).

Figure 6-1 shows the test data plotted by pre-exposure treatment type versus fire endurance of the concrete specimens. The values display that the fire endurance in group 3 is significantly higher than other groups and that there is a large range of overlap of fire endurance between groups 1 and 2. Comparing the residual fire endurance of groups 1 and 2 to the fire endurance of group 3, the fire endurance loss range is 18.3 - 33.05%.

Table 6-8: Results of ANOVA on fire endurance test data under three-treatment one-way classification model

Source	DF	Sum of Squares	F Value	Pr > F
Model	2	1751.99176573	21.22	0.0001*
Error	23	949.48977273		
Corrected Total	25	2701.48153846		

R-Square	C.V.	TR Mean
0.648530	7.831838	82.03846154

* Significant at α level of 0.05

Table 6-9: Student-Newman-Keuls test for mean fire endurance

Student-Newman-Keuls test for variable: TR

Alpha= 0.05 df= 23 MSE= 41.2821

WARNING: Cell sizes are not equal.

Harmonic Mean of cell sizes= 5.910448

Number of Means	2	3
Critical Range	7.7319405	9.360017

Means with the same letter are not significantly different.

SNK Grouping	Mean	N	TREAT
A	104.400	3	3
B	80.755	11	2
B	77.625	12	1

Table 6-10: Duncan's Multiple Range test for mean fire endurance

Duncan's Multiple Range Test for variable: TR

Alpha= 0.05 df= 23 MSE= 41.28216

WARNING: Cell sizes are not equal.

Harmonic Mean of cell sizes= 5.910448

Number of Means	2	3
Critical Range	7.723	8.114

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	TREAT
A	104.400	3	3
B	80.755	11	2
B			
B	77.625	12	1

Table 6-11: Tukey's Studentized Range (HSD) test for mean fire endurance

Tukey's Studentized Range (HSD) Test for variable: TR

Alpha= 0.05 Confidence= 0.95 df= 23 MSE= 41.28216

Critical Value of Studentized Range= 3.542

Comparisons significant at the 0.05 level are indicated by "***".

TREAT Comparison	Simultaneous Lower Confidence Limit	Difference Between Means	Simultaneous Upper Confidence Limit	
3 - 2	13.165	23.645	34.126	***
3 - 1	16.389	26.775	37.161	***
2 - 3	-34.126	-23.645	-13.165	***
2 - 1	- 3.587	3.130	9.846	
1 - 3	-37.161	-26.775	-16.389	***
1 - 2	- 9.846	- 3.130	3.587	

Note: See Table 6-7 for description of treatments 1, 2 & 3.

Table 6-12: Scheffe's test for mean fire endurance

Scheffe's test for variable: TR

Alpha= 0.05 Confidence= 0.95 df= 23 MSE= 41.28216

Critical Value of F= 3.42213

Comparisons significant at the 0.05 level are indicated by '***'.

TREAT Comparison	Simultaneous Lower Confidence Limit	Difference Between Means	Simultaneous Upper Confidence Limit	
3 - 2	12.697	23.645	34.594	***
3 - 1	15.925	26.775	37.625	***
2 - 3	-34.594	-23.645	-12.697	***
2 - 1	- 3.887	3.130	10.146	
1 - 3	-37.625	-26.775	-15.925	***
1 - 2	-10.146	- 3.130	3.887	

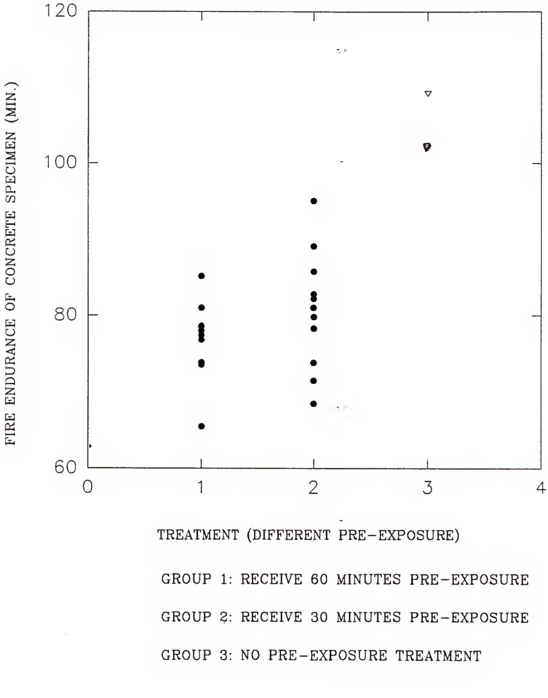

Figure 6-1: Test data plotted by pre-exposed treatment vs. fire endurance of concrete specimen

6.1.4 Comments on Test Results

The original purpose of the experimental design was to investigate how external factors affect the fire resistive ability of burned concrete elements. The three factors[3] in this study were selected because they represent possible situations that might be faced by an investigator. The first factor was simulated by using ASTM E-119 standard temperature course. The second factor was selected as time lapses of 30 days and 75 days. The third factor was simulated by storing the specimens in two environments with different moisture conditions. Once the concrete specimen was burned at a given severity level, it was moved to outdoor conditions under a cover or to a conditioning room for a time lapse of either 30 days or 75 days. The re-curing methods (i.e., storing environments) resulted in different moisture conditions. This situation required that the measured fire endurance of the concrete slabs had to be corrected by standard procedures provided by ASTM E-119[4] for the nonstandard moisture content level. Therefore, the effect of re-curing methods was eliminated by the adjustment procedures. The fire endurance, before adjustment, is summarized in Table 6-13.

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[3] See discussion in section 1.2 of Chapter 1.

[4] For consistency, the entire test procedure followed the ASTM E-119 requirements including the correction for nonstandard moisture content within concrete specimens.

The overall means of fire endurance of 23 burned concrete slabs before adjustment is 77.66 minutes with a standard deviation of 6.41 minutes. The average fire endurance in each observation cell is summarized in Table 6-14.

The procedures in 6.1.2 were repeated for investigating the effect of moisture correction procedures as required in ASTM E-119. The ANOVA model discussed in Chapter 5 was applied to the fire endurance data before adjustment for nonstandard moisture content. Results of ANOVA and GLM procedures are summarized in Table 6-15 and Table 6-16, respectively. Table 6-15 and 6-16 detected a significant difference existed among the treatments. The effect of re-curing method is significant, which is different from the conclusion based upon the fire endurance data after adjustment. In other words, the type of re-curing method significantly affects the fire endurance of the burned concrete specimens. The fire endurance of concrete specimens subjected to the outdoor natural air re-curing is higher than the fire endurance of the specimens that were re-stored in the conditioning room. Therefore, whether or not the burned concrete element can be evaluated properly by using ASTM E-119 test standards is a question that needs further study. It should focus on the effect of the requirement for correction for the nonstandard moisture content.

Table 6-13: Fire endurance of burned concrete specimen before adjustment for moisture content

Pre-exposure Fire Severity	Re-curing Time Lapse			
	30 Days		75 Days	
	Natural Environment Re-curing	Conditioning Room Re-curing	Natural Environment Re-curing	Conditioning Room Re-curing
60 Minutes	77.78 77.23 83.13	75.7 70.33 75.33	76.39 73.12 82.78	61.70 77.24 75.08
30 Minutes	74.51 98.72 77.89	*** 66.99 66.99	85.39 81.55 80.73	84.70 77.77 84.66

*** Missing Specimen

Table 6-14: Average fire endurance of each observation cell before adjustment

Observation Cell	Number of Experimental Unit	Mean of Residual Fire Endurance (minute)	Standard Deviation (minute)
Tr_{111}	3	79.380	3.259
Tr_{121}	3	73.787	2.999
Tr_{112}	3	77.610	4.866
Tr_{122}	3	71.340	8.418
Tr_{211}	3	83.707	13.111
Tr_{221}	2	66.975	0.021
Tr_{212}	3	82.557	2.488
Tr_{222}	3	82.377	3.990

Table 6-15: Results of ANOVA on the fire endurance test data before adjusting

Source	DF	Sum of Squares	F Value	Pr > F
Model	7	650.41581377	2.26	0.0875
Error	15	616.33851667		
Corrected Total	22	1266.75433043		

R-Square	C.V.	TR Mean
0.513451	8.253856	77.66173913

Source	DF	Anova SS	F Value	Pr > F
S	1	114.11007513	2.78	0.1164
M	1	249.21660922	6.07	0.0264*
T	1	16.42534786	0.40	0.5367
S*M	1	0.00000000	0.00	1.0000
S*T	1	77.99597078	1.90	0.1885
M*T	1	81.59894335	1.99	0.1792
S*M*T	1	124.29570801	3.03	0.1025

* Significant at α level of 0.05

Table 6-16: Results of ANOVA (GLM procedures) on the fire endurance test data before adjusting

Source	DF	Sum of Squares	F Value	Pr > F
Model	7	650.41581377	2.26	0.0875
Error	15	616.33851667		
Corrected Total	22	1266.75433043		
R-Square		C.V.	TR Mean	
0.513451		8.253856	77.66173913	

Source	DF	Type III SS	F Value	Pr > F
S	1	64.30764804	1.57	0.2301
M	1	292.23551471	7.11	0.0176*
T	1	35.54160882	0.86	0.3671
S*M	1	8.99494216	0.22	0.6466
S*T	1	120.38094216	2.93	0.1076
M*T	1	88.94669118	2.16	0.1619
S*M*T	1	104.75840098	2.55	0.1312

* Significant at α level at 0.05

6.2 Results of Schmidt Hammer Test

6.2.1 Summary of Test Results

Schmidt rebound hammer test data are listed in Appendix D. These tables include the rebound number measured on each test point prior to first firing, prior to second firing and after the second firing, the percentage loss of rebound number[5] between first and second measurement on each test point, the percentage loss of rebound number between first and third measurement on each test point, the seven-point average percentage loss of rebound number between first and second measurement of each test specimen, and seven-point average percentage loss of rebound number between first and third measurement of each test specimen. Since the percentage loss of rebound number between the first and second measurement is the index for the residual properties of concrete specimen after receiving treatments, theses data were used to analyze the effects of the three main-factor treatments by using the same factorial design as the analysis of the fire endurance test results. Table 6-17 shows the seven-point average percentage loss of rebound number between first and second measurement of each test specimen. The overall mean of the

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[5] The percentage loss of rebound number between two measurements at same point can be calculated by the form: RR % = [(R_2 - R_1) / R_1] * 100. Where, RR % = percentage loss of rebound number of test point; R_1 = rebound number measured prior to first firing; R_2 = rebound number measured prior to second firing.

Table 6-17: Test results of the seven-point average percentage loss (- %) of rebound number between first and second measurement measured on 23 concrete specimens

Pre-exposure Fire Severity	Re-curing Time Lapse			
	30 Days		75 Days	
	Natural Environment Re-curing	Conditioning Room Re-curing	Natural Environment Re-curing	Conditioning Room Re-curing
60 Minutes	15.17 11.93 9.34	-0.56 7.69 12.03	7.19 16.82 5.49	19.60 13.11 11.05
30 Minutes	11.64 7.30 7.93	*** 7.32 7.54	18.01 8.87 6.54	4.69 1.43 3.91

*** Missing Specimen

seven-point average percentage loss of rebound number of 23 concrete specimens is 9.33% with a standard deviation of 5.09%.

6.2.2 Analysis of Test Results

ANOVA was performed on the test results by using the model discussed in Chapter 5. Results of the ANOVA are in Table 6-18, which shows the effects of pre-exposure severity (S), re-curing method (M), re-curing time lapse (T), the interactions, S*M, S*T, and M*T, are not significant, but the interaction S*M*T is significant. In other words, the three main-factor treatments and interactions did not cause significant differences between different levels of treatments.

The General Linear Model procedure was performed due to a missing specimen. Table 6-19 shows the results of ANOVA by using GLM. Though some values in the "sum of square" item are slightly different from the values in Table 6-18, the conclusion drawn from the information in Table 6-18 was not changed.

6.3 Results of Ultrasonic Pulse Velocity Test

6.3.1 Summary of Test Results

Ultrasonic pulse velocity test data are listed in Appendix D, including the pulse transit time (μs) measured on each test point prior to first firing, prior to second firing

Table 6-18: Results of ANOVA on the seven-point average percentage loss (- %) of rebound number between first and second measurement measured on 23 concrete specimens

Source	DF	Sum of Squares	F Value	Pr > F
Model	7	262.13011014	1.83	0.1547
Error	15	307.32593333		
Corrected Total	22	569.45604348		
R-Square		C.V.	RR Mean	
0.460317		48.50103	9.33260870	

Source	DF	Anova SS	F Value	Pr > F
S	1	53.23189727	2.60	0.1278
M	1	38.26254575	1.87	0.1919
T	1	3.92918590	0.19	0.6677
S*M	1	32.91302046	1.61	0.2243
S*T	1	23.79287364	1.16	0.2982
M*T	1	8.94437516	0.44	0.5188
S*M*T	1	101.05621196	4.93	0.0422*

* Significant at α level of 0.05

Table 6-19: Results of ANOVA (GLM procedure) on the seven-point average percentage loss (- %) of rebound number between first and second measurement measured on 23 concrete specimens

Source	DF	Sum of Squares	F Value	Pr > F
Model	7	261.81452754	1.83	0.1553
Error	15	307.41393333		
Corrected Total	22	569.22846087		
R-Square		C.V.	RR Mean	
0.459946		48.51475	9.33130435	

Source	DF	Type III SS	F Value	Pr > F
S	1	53.19407451	2.60	0.1280
M	1	39.08489804	1.91	0.1875
T	1	5.06968235	0.25	0.6261
S*M	1	23.29007451	1.14	0.3033
S*T	1	20.36800392	0.99	0.3346
M*T	1	6.94729804	0.34	0.5691
S*M*T	1	101.72019216	4.96	0.0416*

* Significant at α level 0.05

and after second firing, the percentage loss[6] of pulse velocity between first and the second measurement on each test point, the percentage loss of pulse velocity between first and third measurement on each test point, the seven-point average percentage loss of pulse velocity between first and second measurement of each test specimen, and the seven-point average percentage loss of pulse velocity between first and third measurement of each test specimen. Since the percentage loss of pulse velocity between first and second measurement is the index for the residual properties of concrete specimen after receiving treatments, these data were used to analyze the effects of three main-factor treatments by using the same factorial design as in the fire endurance test. Table 6-20 shows the seven-point average percentage loss of pulse velocity between first and second measurement of each test specimen. The overall mean of the seven-point average percentage loss of pulse velocity between first and second measurement of 23 concrete specimens is 24.46% with a standard deviation of 6.11%.

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[6] The depth of a test point is d which remains a constant after firing, and the pulse velocity can be obtained by using the formula: $v = d / t$, once the transit time is known. Thus, the percentage loss of pulse velocity on each test point can be calculated by using the following equation:

$$VR\ \% = \frac{v_2 - v_1}{v_1} * 100 = \frac{t_1 - t_2}{t_2} * 100 = (\frac{t_1}{t_2} - 1) * 100$$

where, VR % = percentage loss of pulse velocity of test point; t_1 = pulse transit time measured on test point prior to first firing; t_2 = pulse transit time measured on test point prior to second firing.

Table 6-20: Test results of the seven-point average percentage loss (- %) of pulse velocity between first and second measurement measured on 23 concrete specimens

Pre-exposure Fire Severity	Re-curing Time Lapse			
	30 Days		75 Days	
	Natural Environment Re-curing	Conditioning Room Re-curing	Natural Environment Re-curing	Conditioning Room Re-curing
60 Minutes	31.76 30.23 30.18	31.68 32.71 35.52	29.53 30.42 19.40	21.04 26.43 26.78
30 Minutes	22.04 19.52 24.64	*** 18.30 18.04	23.21 16.01 14.72	23.15 17.18 20.14

*** Missing Data

6.3.2 Analysis of Test Results

The ANOVA was conducted and the results are listed in Table 6-21. It can be seen that the effects of pre-exposure severity (S) and re-curing time lapse (T) are significant, while the effects of re-curing method (M), and interactions S*M, S*T, M*T, and S*M*T are not significant. The mean value of the seven-point average percentage loss of pulse velocity between first and second measurement of the concrete specimens subjected to the 60-minute pre-exposure severity is 28.81% with a standard deviation of 4.70%. The mean value of the seven-point average percentage loss of pulse velocity between first and second measurement of the concrete specimens subjected to the 30-minute pre-exposure severity is 19.72% with a standard deviation of 3.22%. The approximate t-test at the 0.05 level of significance was used to compare these two values. Since the calculated test statistic, 5.445, is greater than the t-table value, 1.734, at df= 18, $\alpha = 0.05$, it is concluded that the seven-point average percentage loss of pulse velocity between first and second measurement in the 60-minute group is significantly greater than the seven-point average percentage loss of pulse velocity between first and second measurement in 30-minute group.

The mean value of the seven-point average percentage loss of pulse velocity between first and second measurement of the concrete specimens subjected to the 30-day re-curing time lapse is 26.78% with a standard deviation of 6.42%. The mean

Table 6-21: Results of ANOVA on the seven-point average percentage loss (- %) of pulse velocity between first and second measurement on 23 concrete specimens

Source	DF	Sum of Squares	F Value	Pr > F
Model	7	642.27372464	7.73	0.0005*
Error	15	177.99566667		
Corrected Total	22	820.26939130		
R-Square		C.V.	VR Mean	
0.783003		14.08199	24.46217391	

Source	DF	Anova SS	F Value	Pr > F
S	1	473.58130604	39.91	0.0001*
M	1	0.61983676	0.05	0.8223
T	1	113.62204509	9.58	0.0074*
S*M	1	1.15376809	0.10	0.7595
S*T	1	15.42314309	1.30	0.2721
M*T	1	1.54427612	0.13	0.7233
S*M*T	1	36.32934903	3.06	0.1006

* Significant at α level of 0.05

value of the seven-point average percentage loss of pulse velocity between first and second measurement of the concrete specimens subjected to the 75-day re-curing time lapse is 22.33% with a standard deviation of 5.18%. The approximate t-test at the 0.05 level of significance was used to compare these two values. Since the calculated test statistic, 1.820, is greater than the t-table value, 1.725, at df= 20, $\alpha = 0.05$, it is concluded that the seven-point average percentage loss of pulse velocity between first and second measurement in the 30-day group is significantly greater than the seven-point average percentage loss of pulse velocity between first and second measurement in the 75-day group.

Since there is a missing data set, the appropriate General Linear Model procedure of SAS was performed to verify the results of ANOVA and the results are shown in Table 6-22. As may be seen, the conclusion drawn from Table 6-21 remained unchanged..

6.4 Hypotheses Validity Summary

This section is a review of the statistical hypotheses presented in Chapter 5 and a summary of their evaluation from this research.

6.4.1 Fire Endurance Test

H_1: "There are significant interactions among different 3-factor combination effects (pre-exposure severity * re-

Table 6-22: Results of ANOVA (GLM procedure) on the seven-point average percentage loss (- %) of pulse velocity between first and second measurement measured on 23 concrete specimens

Source	DF	Sum of Squares	F Value	Pr > F
Model	7	642.27372464	7.73	0.0005*
Error	15	177.99566667		
Corrected Total	22	820.26939130		

R-Square	C.V.	VR Mean
0.783003	14.08199	24.46217391

Source	DF	Type III SS	F Value	Pr > F
S	1	473.58130646	39.91	0.0001*
M	1	0.04084040	0.00	0.9540
T	1	93.73242861	7.90	0.0132
S*M	1	0.69440531	0.06	0.8121
S*T	1	35.89569201	3.02	0.1025
M*T	1	0.49676381	0.04	0.8406
S*M*T	1	37.83229804	3.19	0.0944

* Significant at α level of 0.05

curing method * re-curing time lapse)" was rejected at the 95% level of confidence and it was concluded that no significant interactions existed.

H_2: "There are significant interactions among different 2-factor combination effects (pre-exposure severity * re-curing method)" was rejected at 95% level of confidence and it was concluded that no significant interactions existed.

H_3: "There are significant interactions among different 2-factor combination effects (pre-exposure severity * re-curing time lapse)" was rejected at the 95% level of confidence and it was concluded that no significant interactions existed.

H_4: "There are significant interactions among different 2-factor combination effects (re-curing method * re-curing time lapse)" was rejected at the 95% level of confidence and it was concluded that no significant interactions existed.

H_5: "There is a significant difference in fire endurance of burned concrete slabs between the two levels of pre-exposure severity" was rejected at the 95% level of confidence and it was concluded that no significant interactions existed.

H_6: "There is a significant difference in fire endurance of burned concrete slabs between the two levels of re-curing method" was rejected at the 95% level of confidence and it was concluded that there was no significant difference.

H_7: "There is a significant difference in fire endurance of burned concrete slabs between the two levels of re-curing

time lapse" was rejected at the 95% level of confidence and it was concluded that there was no significant difference.

H_8: "There is a significant differences in fire endurance of burned concrete slabs between experimental groups and control group" was accepted at the 95% confidence level of significance with four kinds of multiple comparison tests.

6.4.2 Schmidt Rebound Hammer Test

H_1: "There are significant interactions among different 3-factor combination effects (pre-exposure severity * re-curing method * re-curing time lapse)" was accepted at the 95% level of confidence.

H_2: "There are significant interactions among different 2-factor combination effects (pre-exposure severity * re-curing method)" was rejected at the 95% level of confidence and it was concluded that there was no significant interaction.

H_3: "There are significant interactions among different 2-factor combination effects (pre-exposure severity * re-curing time lapse)" was rejected at the 95% level of confidence and it was concluded that there was no significant interaction.

H_4: "There are significant interactions among different 2-factor combination effects (re-curing method * re-curing time lapse)" was rejected at the 95% level of confidence and it was concluded that there was no significant interaction.

H_5: "There is a significant difference in the seven-point average percentage loss of rebound numbers between the two levels of pre-exposure severity" was rejected at the 95% level of confidence and it was concluded that there was no significant difference.

H_6: "There is a significant difference in the seven-point average percentage loss of rebound numbers between the two levels of re-curing method" was rejected at the 95% level of confidence and it was concluded that there was no significant difference.

H_7: "There is a significant difference in the seven-point average percentage loss of rebound numbers between the two levels of re-curing time lapse" was rejected at the 95% level of confidence and it was concluded that there was no significant difference.

6.4.3 Ultrasonic Pulse Velocity

H_1: "There are significant interactions among different 3-factor combination effects (pre-exposure severity * re-curing method * re-curing time lapse)" was rejected at the 95% level of confidence and it was concluded that there was no significant interaction.

H_2: "There are significant interactions among different 2-factor combination effects (pre-exposure severity * re-curing method)" was rejected at the 95% level of confidence and it was concluded that was no significant interaction.

H_3: "There are significant interactions among different 2-factor combination effects (pre-exposure severity * re-curing time lapse)" was rejected at the 95% level of confidence and it was concluded that there was no significant interaction.

H_4: "There are significant interactions among different 2-factor combination effects (re-curing method * re-curing time lapse)" was rejected at the 95% level of confidence and it was concluded that there was no significant interaction.

H_5: "There is a significant difference in the seven-point average percentage loss of pulse velocities between the two levels of pre-exposure severity" was accepted at the 95% level of confidence.

H_6: "There is a significant difference in the seven-point average percentage loss of pulse velocities between the two levels of re-curing method" was rejected at the 95% level of confidence and it was concluded that there was no significant difference.

H_7: "There is a significant difference in the seven-point average percentage loss of pulse velocities between the two levels of re-curing time lapse" was accepted at the 95% level of confidence.

CHAPTER 7
DISCUSSION AND CONCLUSION

7.1 Major Findings

7.1.1 Research Hypothesis Validity Summary

The research hypotheses validated as a results of this study are: 1. "Residual fire endurance and compressive strength of burned concrete elements will be reduced by severe fire exposure" was accepted based on the analysis of test results in Chapter 6.

2. "The relationships between test results of nondestructive and destructive tests can be established" was accepted based on the discussions in Appendix F.

7.1.2 Explanation of the Results

The fire endurance of concrete slabs in the control group (i.e., concrete slabs which did not receive pre-exposure treatment) is significantly higher than the fire endurance of experimental groups (i.e., concrete slabs which were subjected to pre-exposure treatment) but no significant difference was detected between 30-minute and 60-minute pre-exposure treatment groups. The pre-burned concrete slabs have a

reduced fire endurance about 6.64 - 25.2% before adjustment for moisture content and about 18.3 - 33.05% after adjustment.

This phenomenon was attributed to the absorption of latent heat associated with the dehydration reactions taking place in the Portland cement paste. It is indicated (Lie 1972) that the significant removal of free water from the pores in the concrete starts at about 212°F and at about the same temperatures removal of water of crystallization (dehydration) from cement paste begins. The rate of dehydration of cement varies at different temperatures. If the heating rate is set at 9°F per minute, when the temperature reaches about 1,200°F, the rate of dehydration increases considerably. After that point, most of the water of crystallization (nonvaporable water) is removed from the components[1] of cement, which is an irreversible reaction. In this research, the heating rate is higher than 9°F per minute and, even for the 30 minutes pre-exposure, the temperature exceeded 1,200°F. Therefore, the atmospheric moisture reabsorbed by the pre-burned concrete slabs after first firing[2] did not contribute significantly to fire endurance

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[1] The two main components in cement paste are: (1) 1.62 $CaO \cdot Si_2 \cdot 1.5\ H_2O$, commonly refereed to as tobermorite gel and (2) $CaO \cdot H_2O$.

[2] The temperature of fire test furnace was more than 1,500°F at 30 minutes after ignition which is significantly higher than the critical temperature for dehydration of Portland cement paste.

even though the relative humidity of the test slabs exceeded the relative humidity level of the control group.

ASTM E-119 is the only standard adopted for measuring fire endurance of building elements and materials and the standard time-temperature curve in ASTM E-119 was created to simulate a real building fire. It is very difficult to estimate the time and temperature in a real fire, therefore, using ASTM E-119 simulation can obtain reasonable fire history. In general, if a fire only lasts for less than 30 minutes its effects on structures should be considered insignificant. Thus, the research results indicate that once the concrete slabs are exposed to a building fire for more than 30 minutes the fire endurance will decrease about 25% (the average decrease of fire endurance is 25.65% in 60-minute group and 22.65% in 30-minute group). Although the decrease of compressive strength of concrete slabs after fire cannot be quantitatively measured by using nondestructive methods due to the lack of test data from the cores of pre-burned slabs prior to second firing, it is obvious that the nondestructive test data show some qualitative changes (see Appendix D).

7.2 Discussion

7.2.1 Discussion on the Three Main-Factor Treatments

The purpose of this study is to investigate how certain external factors affect the residual fire endurance and residual compressive strength of burned concrete. The

problems studied include: (a) Can we determine the intensity and duration of a fire that has occurred in a structure?; (b) Can the concrete strength be regained or grow continuously with time after fire?; and (c) How does re-absorption of moisture in concrete affect the fire endurance?. The three main-factor (i.e., pre-exposure severity, re-curing method, and re-curing time lapse) treatments were studied in a 2 X 2 X 2 factorial experimental design.

The following is a review of the effects of these three main-factor treatments involved in this study.

1. The pre-exposure severity was to simulate a real fire in accordance with ASTM E-119 standard time-temperature curve. The exposure time period were selected as ⅓ and ⅔, of the average fire endurance of concrete slabs in the control group[3]. For convenience and approximation, the exposure time periods were established at 30 minutes and 60 minutes. One third of the fire endurance of the control group was chosen (approximately equal to 30 minutes) because a shorter fire exposure time would, generally, not cause severe damage to structure members and in turn should not be of major concern for consideration for reuse of the building.

   It is known (Abrams 1973, Abrams 1977) that a critical temperature to the carbonate-aggregate concrete is around

[3] The average fire endurance is 104.4 minutes after adjustment.

1,250°F. Once this temperature is exceeded, the strength of the concrete will be significantly reduced and other properties (i.e., thermal expansion, modulus of elasticity) will be affected. In this design, the exposure surface of all burned concrete slabs (including both the 60-minute and 30-minute pre-exposure severity groups) were exposed to temperatures higher than the critical temperature, 1,250°F. Exceeding this critical temperature can be used to explain the results of ANOVA of the data from the different test techniques. The results of the ANOVA indicated no significant difference between the two levels of pre-exposed severity.

Therefore, for concrete slabs (4 inches thick, no reinforcement, and no load) subjected to 30 minutes of exposure (after flashover) and/or 1,500°F temperature can be taken as an indicator that the remaining fire resistive capability may be reduced to approximately 75% of the original fire endurance.

2. The re-curing method treatment was designed to subject the pre-exposed concrete slabs to different moisture conditions following fire exposure. However, the effect of this treatment was off-set by the adjustment for nonstandard moisture content required in the ASTM E-119 standard. The ANOVA results indicated that the re-curing methods made no significant difference in adjusted fire

endurance but caused significant differences according to the unadjusted fire endurance.

3. The re-curing time-lapse treatment was designed to store the pre-exposed concrete slabs for a time lapse of 30 days and 75 days. Lie (1972) indicated that the behavior of the modulus of elasticity of concrete, which parallels the compressive strength, will recover substantially with time, if the concrete has not been heated above 930°F. In this study, the furnace temperatures were higher than 930°F. Exceeding this critical temperature may have caused the lack of significance in the results of ANOVA of the test data from the different test techniques.

7.2.2 Discussion on the Adjustments for Fire Endurance

Among the common inorganic building materials, only the hydrated Portland cement products can hold (after due conditioning in accordance with in section 11 in ASTM E-119) a sufficient amount of moisture to affect the results of fire tests noticeably. Consequently, ASTM E-119 requires correcting the experimental fire endurance data of constructions containing more than 5% volume of Portland cement with nonstandard moisture content. However, adjustment for moisture content created two situations in this investigation that warrant further study to investigate whether this requirement is appropriate.

The furnace temperatures were affected significantly by the relative humidity level of test specimens during the fire test. Normally, under the same control procedures and equipment configuration, test specimens with lower relative humidity (i.e., about 40% or less) cause furnace temperatures to get higher than the prescribed ASTM E-119 temperature. In contrast, test specimens with higher relative humidity (i.e., about 75% or greater) cause the furnace temperatures to remain lower than the ASTM E-119 temperature. According to the requirements in ASTM E-119, the test results should be corrected for the nonstandard furnace temperature and nonstandard moisture content. Therefore, when using very sensitive test equipment, the test results might be over corrected.

According to the experimental design, all 23 concrete specimens were subjected to either 60-minute or 30-minute pre-exposure treatment. Since the first firing brought some permanent changes in the properties of the concrete, the pre-burned concrete specimens ought to be treated as if they were made from a different material. This action is especially true because the nonvaporable water was never regained after pre-exposure. This water is the major source of moisture content that contributes to the absorption of latent heat associated with the dehydration reactions during the fire test. Therefore, the correction procedures for nonstandard

moisture content may not be appropriate for the pre-burned concrete elements.

7.3 Use of Nondestructive Test Methods to Evaluate Fire Endurance

In general, high-strength concrete has higher fire endurance than low strength concrete. The test data show that while the fire endurance of concrete slabs decreases after fire, so does the strength. Therefore, it is of interest to investigate the possibility of using the nondestructive test methods employed in this study to evaluate residual fire endurance of concrete slabs.

A statistical analysis for comparing fire endurance and nondestructive test data is presented in Appendix E. Although no definite conclusion can be reached in this particular investigation, the analysis does give encouraging implication that it is feasible to use nondestructive pulse velocity test to evaluate the residual fire endurance. Further detailed experimental research is definitely needed.

7.4 Relationship between the Results of Nondestructive and Destructive Test Methods

Statistical test results in Appendix F indicated that the linear correlation between the percentage loss of Schmidt hammer rebound number and the percentage loss of drilled core compressive strength was not significant. This result precluded establishment of a linear regression model that

could be used to predict the decrease of compressive strength of burned concrete elements by using Schmidt rebound hammer. The variation in the results was too great to detect a significant relationship between the two test methods. Other researchers[4] have reported large variation in the accuracy of predicted concrete strength. It was concluded that the Schmidt rebound hammer test not be recommended for use as a nondestructive method for assessing compressive strength of burned concrete elements. More rigorous experimental designs using more accurate instrumentation combined with other nondestructive test methods may be able to reduce the unexplained variation and improve the ability to identify the relationship that exists, if any.

However, the analysis results in Appendix F indicated that a linear relationship existed between the average percentage loss of ultrasonic pulse velocity and the percentage loss of drilled core compressive strength. This result indicates that ultrasonic pulse velocity testing can be used for the field investigation of fire damage. The procedure would involve comparing the pulse velocities transitted through damaged and undamaged concrete elements in the structure to estimate the percentage loss of compressive strength in the fire-damaged concrete elements.

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[4] The accuracy of prediction of concrete strength in a structure is about ± 25% (Malhorta 1976).

It is believed that using a combination of two or more nondestructive test methods may give satisfactory results. The analysis indicates that if removal of some outlier points can be justified, a more satisfactory regression might be established.

7.5 Reuse of Building after Fire

There have been many discussions on repair of fire damaged concrete structural members in a building to maintain their design load carrying capacity. However, because the current building code does not address the issue of residual fire endurance of structural members after a building fire, there is an open territory for scientific study. If the re-build cost is excessive or if it will cause disruption to the operations of the facilities, the owner may want to repair the fire damaged building rather than to re-build it. To keep the fire damaged building in compliance with current code requirements for fire safety, and to achieve economical repair, and to minimize interruption of the operations of facilities, the repaired performance of concrete elements must be successfully evaluated by some standards. The equivalency concepts based on a "performance code" must be adopted to overcome the inflexibility of the current "specification code."[5] This approach may be the most reasonable way to

[5] The performance code do not describe dimensions, materials, finishes or methods of manufacture or assembly; rather they describe the performance required by the user.

achieve the goal of effectively repairing the fire damaged buildings.

It is suggested that the fire safety requirements must be rewritten to deal with performance rather than specification criteria. Under the concepts of performance codes, a building is described as a multi-functional agent of environmental change that has to achieve adequate and acceptable performance so that a safe and comfortable environment will result for any human activity. Because of the demands for higher performance of a whole building, there is a trend toward moving away from the immensely detailed and fairly inflexible system of statutory building controls to a set of shorter, boarder functional regulations supported by precise statutory performance codes or standards. Therefore, this type of research should be considered as a key to encourage the authorities to consider performance code.

7.6 Conclusions

As a preliminary and pilot study, this research is the first study conducted by using a combination experimental design consisting of a statistical method and a standard fire test method to investigate the residual fire endurance of burned concrete elements. Two nondestructive tests and one destructive test were selected to evaluate the fire damage of

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Simply state any material, composite, component or building must be fit for its intended purpose.

concrete slabs along with same factorial design in the fire endurance test. The following conclusions are reached from this research.

1. The research results show that once a fire lasts for 30 minutes and/or reach temperature 1,500°F, the residual fire endurance decreases 25%. Although there are no quantitative results[6] for reduction of residual compressive strength in burned concrete slabs. The final core compressive strength data indicate that a decrease of compressive strength exist.
2. Once a fire lasts for 30 minutes or longer and reaches 1,500°F or higher temperature, the effects of pre-exposure severity, re-curing methods, and the re-curing time lapse are not significant. However, the required fire endurance adjustment for moisture content by ASTM E-119 change the test results. Therefore, whether the adjustment requirement is appropriate needs further investigation.
3. The validity of using nondestructive methods for evaluation of fire damage is inconclusive. However, the test data imply that the nondestructive test methods, especially, the ultrasonic pulse velocity test can be used to evaluate not only the residual compressive

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[6] Due to the limitation of experimental sample size, no core sample were taken from concrete slabs after first firing. Therefore, there are no residual core compressive test data in this study.

strength but also the residual fire endurance of concrete slabs after fire.

4. The experiments conducted in this study revealed the imperfectness of ASTM E-119 standard time-temperature. It is obvious that some basic studies have to be conducted in the future.
5. Although there are many limitations in using a small-scale furnace to conduct research, it was shown to be a feasible tool for use in a pilot fire test to obtain some important information. However, for more realistic results, a full-scale test furnace and specimen should be employed in further studies.
6. Generally, standard fire test only requires a single test, but replicate tests would be needed for any statistical analyses which could generate more conclusive results.

7.7 Recommended Further Research

Based on this study, it is suggested that the following research should be conducted as an extension of this work:

1. Repeat this research by using a full-scale fire test including loading and boundary constraints.
2. Conduct a similar small-scale test replacing the ASTM E-119 pre-exposure fire severities by fixed times and at constant temperatures (such as 5 minutes - 300°F, 10 minutes - 600°F, 15 minutes - 1,000°F) to investigate the

correlations between different factors on the residual fire endurance and strength, because the lower pre-exposure temperature may cause the concrete to re-absorb moisture with time and the concrete may regain its fire endurance and strength. This may deviate from the simulation of ASTM E-119 to real fire.

3. Repeat the experiment with drilled core samples taken from concrete after the first firing to collect complete data.
4. Conduct an analysis with combined effects of Schmidt rebound hammer test and ultrasonic pulse velocity test to investigate the validity of combined tests.
5. Conduct a test to further verify the ASTM E-119 requirement of fire endurance adjustment for moisture content by using more precise and sophisticated equipment and by calculating all heat transfer that occurring in the furnace and specimens.
6. Conduct a study to investigate the use of ultrasonic pulse velocity test for evaluating residual fire endurance of concrete structural elements.
7. Conduct a comprehensive nondestructive test on concrete cylinders exposed to fire of different time period and temperature levels, by using the Schmidt hammer test, the ultrasonic pulse velocity test, and standard compressive test to create calibration data for each nondestructive test.

8. Conduct a similar nondestructive test on concrete slabs by using data obtained in the above method (No.7).

APPENDIX A
SUMMARY OF FIRE ENDURANCE TEST DATA OF BURNED CONCRETE SLABS

Specimen	Ambient Condition before First Fire Test		Measured Concrete Temp. & RH before First Fire Test		Test Duration of Fire Test (Based on ASTM E-119 Curve) (minute)	Re-Curing Condition after First Fire Test	Re-Curing Timelapse after First Fire Test (day)	Ambient Condition of the day Second Test		Measured Concrete Temp. & RH of the day Second Test		Fire Endurance of Second Fire Test (minute)		Adjusted Fire Endurance (minute) (Based on Moisture Content)
	Temp. F	RH (%)	Temp. F	RH (%)	Test Condition			Temp. F	RH (%)	Temp. F	RH (%)	Test Condition	Standard Condition	
TR000 - A								72.0	52.8	73.2	38.5	90.23	87.23	102.0
TR000 - B								70.7	81.0	74.7	45.6	90.96	87.77	102.0
TR000 - C								68.7	82.2	67.5	44.2	95.10	93.95	109.2
TR111 - A	64.8	26.6	65.4	51.1	60	Outdoor	30	81.0	45.2	80.0	83.5	79.77	77.78	76.8
TR111 - B	68.6	35.2	64.1	49.6	60	Outdoor	30	80.4	37.3	80.6	73.2	78.17	77.23	78.0
TR111 - C	72.4	46.9	71.5	42.5	60	Outdoor	30	83.7	38.5	79.7	62.6	85.03	83.13	85.2
TR121 - A	67.2	47.1	66.1	49.1	60	Conditioned Room	30	69.2	30.1	65.9	49.9	76.53	75.70	78.6
TR121 - B	71.6	61.0	71.0	55.1	60	Conditioned Room	30	72.8	35.7	68.3	41.7	71.03	70.33	73.8
TR121 - C	73.5	42.2	76.0	56.4	60	Conditioned Room	30	80.5	33.5	83.4	58.5	76.33	75.33	78.0
TR112 - A	67.9	28.7	66.3	29.7	60	Outdoor	75	84.8	22.3	84.0	72.2	78.37	76.93	77.4
TR112 - B	68.0	89.6	66.4	31.1	60	Outdoor	75	69.0	43.0	66.6	73.5	74.50	73.12	73.5
TR112 - C	73.1	83.0	74.9	53.8	60	Outdoor	75	78.3	40.0	75.1	59.5	82.97	82.78	85.2
TR122 - A	74.5	33.0	72.9	58.0	60	Conditioned Room	75	79.4	71.0	80.5	46.7	62.80	61.70	65.4
TR122 - B	79.0	39.2	78.2	42.2	60	Conditioned Room	75	89.4	32.5	87.1	37.9	77.17	77.24	81.0
TR122 - C	79.0	51.7	73.2	46.0	60	Conditioned Room	75	79.5	60.2	82.0	49.0	75.77	75.08	78.6
TR211 - A	77.4	50.7	76.9	58.3	30	Outdoor	30	76.7	57.9	77.2	76.8	76.80	74.51	73.8
TR211 - B	71.1	32.6	72.5	55.1	30	Outdoor	30	76.2	73.8	73.4	90.1	99.67	98.72	95.1
TR211 - C	72.1	53.1	70.3	48.1	30	Outdoor	30	83.9	37.4	82.6	74.5	80.00	77.89	78.3
TR221 - A	70.1	67.9	70.6	47.3		(This Specimen broke down after First Firing, Missing Data)								
TR221 - B	68.8	57.4	68.6	49.7	30	Conditioned Room	30	69.7	36.8	69.7	69.4	68.50	66.99	68.4
TR221 - C	77.7	30.6	74.0	48.5	30	Conditioned Room	30	68.9	30.0	71.2	44.1	69.37	66.96	71.4
TR212 - A	69.9	54.0	71.3	31.5	30	Outdoor	75	83.0	37.8	82.6	95.8	87.13	85.39	82.8
TR212 - B	61.2	40.0	59.5	40.0	30	Outdoor	75	82.7	41.5	80.3	69.3	82.70	81.55	82.8
TR212 - C	67.6	30.0	67.3	48.2	30	Outdoor	75	78.4	58.8	76.6	80.9	81.90	80.73	79.8
TR222 - A	47.1	35.6	48.6	49.1	30	Conditioned Room	75	89.1	42.6	88.5	67.4	84.85	84.70	85.8
TR222 - B	57.2	32.0	58.6	47.6	30	Conditioned Room	75	87.2	42.6	87.8	53.5	79.17	77.77	81.0
TR222 - C	61.6	43.3	60.7	43.9	30	Conditioned Room	75	87.1	45.6	86.8	42.2	85.17	84.66	89.1

APPENDIX B
CORRECTING DATA FOR FIRE ENDURANCE OF NONSTANDARD MOISTURE CONTENT OF CONCRETE SPECIMENS

# OF SPECIMEN	RH (%)	A	Me	Mc	Ma	Ms	B	BMa	BMs	TR' (MIN.)*	TR'(HR)*	TR' % LOSS	TR" (HR)**	TR" (MIN.)	TR" % LOSS
TR000_A	38.5	0	0.15	0	0	0.0432	5.5	0	0.2376	87.23	1.45	89.65	1.7	102	104.4
TR000_B	45.6	0	0.1615	0	0	0.0432	5.5	0	0.2376	87.77	1.46		1.7	102	
TR000_C	44.2	0	0.1584	0	0	0.0432	5.5	0	0.2376	93.95	1.57		1.82	109.2	
TR111_A	83.5	1	0.269	0.269	0.04842	0.0432	5.5	0.26631	0.2376	77.78	1.30	-13.24%	1.28	76.8	-26.44%
TR111_B	73.2	1	0.2346	0.2346	0.042228	0.0432	5.5	0.232254	0.2376	77.23	1.29	-13.85%	1.3	78	-25.29%
TR111_C	62.6	1	0.2025	0.2025	0.03645	0.0432	5.5	0.200475	0.2376	83.13	1.39	-7.27%	1.42	85.2	-18.39%
TR121_A	49.9	1	0.175	0.175	0.0315	0.0432	5.5	0.17325	0.2376	75.7	1.26	-15.56%	1.31	78.6	-24.71%
TR121_B	41.7	1	0.1536	0.1536	0.027648	0.0432	5.5	0.152064	0.2376	70.33	1.17	-21.55%	1.23	73.8	-29.31%
TR121_C	58.5	1	0.192	0.192	0.03456	0.0432	5.5	0.19008	0.2376	75.33	1.26	-15.97%	1.3	78	-25.29%
TR112_A	72.2	1	0.2316	0.2316	0.041688	0.0432	5.5	0.229284	0.2376	76.93	1.28	-14.19%	1.29	77.4	-25.86%
TR112_B	73.5	1	0.2355	0.2355	0.04239	0.0432	5.5	0.233145	0.2376	73.12	1.22	-18.44%	1.225	73.5	-29.60%
TR112_C	59.5	1	0.194	0.194	0.03492	0.0432	5.5	0.19206	0.2376	82.78	1.38	-7.66%	1.42	85.2	-18.39%
TR122_A	46.7	1	0.1654	0.1654	0.029772	0.0432	5.5	0.163746	0.2376	61.7	1.03	-31.18%	1.09	65.4	-37.36%
TR122_B	37.9	1	0.15	0.15	0.027	0.0432	5.5	0.1485	0.2376	77.24	1.29	-13.84%	1.35	81	-22.41%
TR122_C	49	1	0.172	0.172	0.03096	0.0432	5.5	0.17028	0.2376	75.08	1.25	-16.25%	1.31	78.6	-24.71%
TR211_A	76.8	1	0.2454	0.2454	0.044172	0.0432	5.5	0.242946	0.2376	74.51	1.24	-16.89%	1.23	73.8	-29.31%
TR211_B	90.1	1	0.3	0.3	0.054	0.0432	5.5	0.297	0.2376	98.72	1.65	10.12%	1.585	95.1	-8.91%
TR211_C	74.5	1	0.2385	0.2385	0.04293	0.0432	5.5	0.236115	0.2376	77.89	1.30	-13.12%	1.305	78.3	-25.00%
TR221_A	---	---	---	---	---	0.0432	5.5	---	0.2376	---	---	---	---	---	---
TR221_B	69.4	1	0.2232	0.2232	0.040176	0.0432	5.5	0.220968	0.2376	66.99	1.12	-25.28%	1.14	68.4	-34.48%
TR221_C	44.1	1	0,158	0.158	0.02844	0.0432	5.5	0.15642	0.2376	66.96	1.12	-25.31%	1.19	71.4	-31.61%
TR212_A	95.8	1	0.3	0.3	0.054	0.0432	5.5	0.297	0.2376	85.39	1.42	-4.75%	1.38	82.8	-20.69%
TR212_B	69.3	1	0.2232	0.2232	0.040176	0.0432	5.5	0.220968	0.2376	81.55	1.36	-9.04%	1.38	82.8	-20.69%
TR212_C	80.9	1	0.259	0.259	0.04662	0.0432	5.5	0.25641	0.2376	80.73	1.35	-9.95%	1.33	79.8	-23.56%
TR222_A	67.4	1	0.2172	0.2172	0.039096	0.0432	5.5	0.215028	0.2376	84.7	1.41	-5.52%	1.43	85.8	-17.82%
TR222_B	53.5	1	0.182	0.182	0.03276	0.0432	5.5	0.18018	0.2376	77.77	1.30	-13.25%	1.35	81	-22.41%
TR222_C	42.4	1	0.1544	0.1544	0.027792	0.0432	5.5	0.152856	0.2376	84.66	1.41	-5.57%	1.485	89.1	-14.66%
ATR333	58.3	0	0.1918	0	0	0.0432	5.5	0	0.2376	103.45	1.72	15.39%	2.05	123	17.82%

* First adjusted fire endurance by non-standard furnace temperature

** Second adjusted fire endurance by non-standard moisture content

APPENDIX C
FIRING DATA OF CONCRETE SPECIMENS DURING FIRE TEST

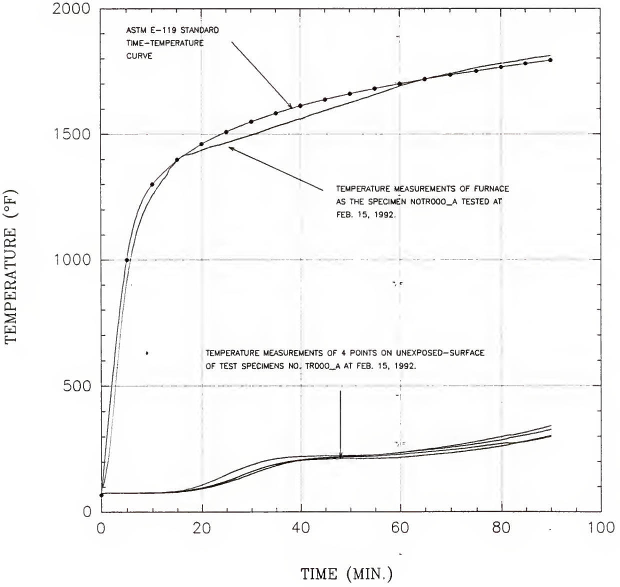

FIGURE C-1: FIRING DATA OF SPECIMEN NO. TR000_A

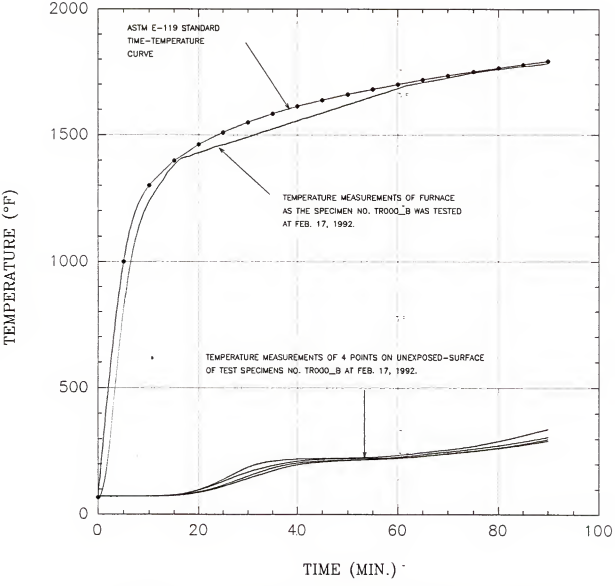

FIGURE C-2: FIRING DATA OF SPECIMEN NO. TR000_B

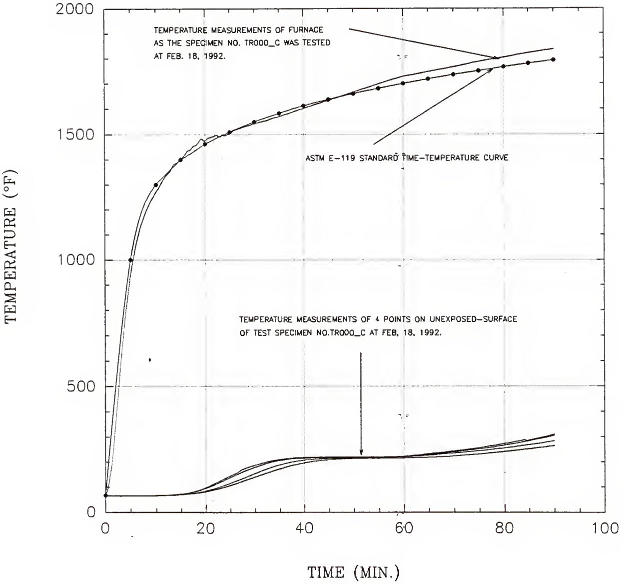

FIGURE C-3: FIRING DATA OF SPECIMEN NO. TR000_C

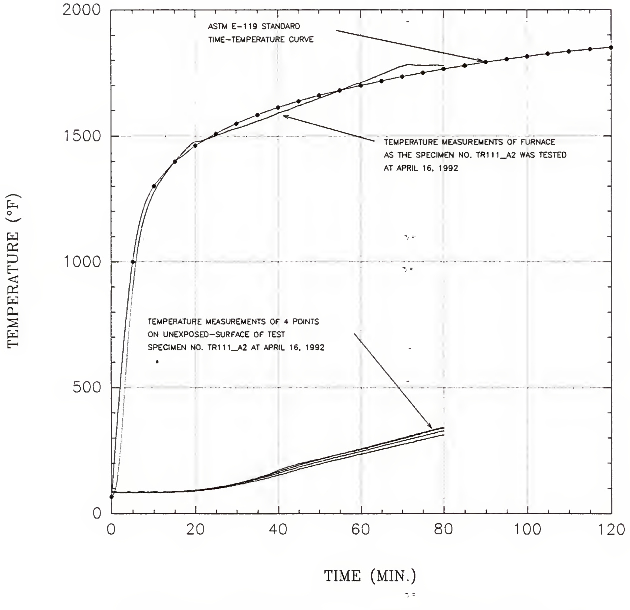

FIGURE C-4: FIRING DATA OF SPECIMEN NO. TR111_A2

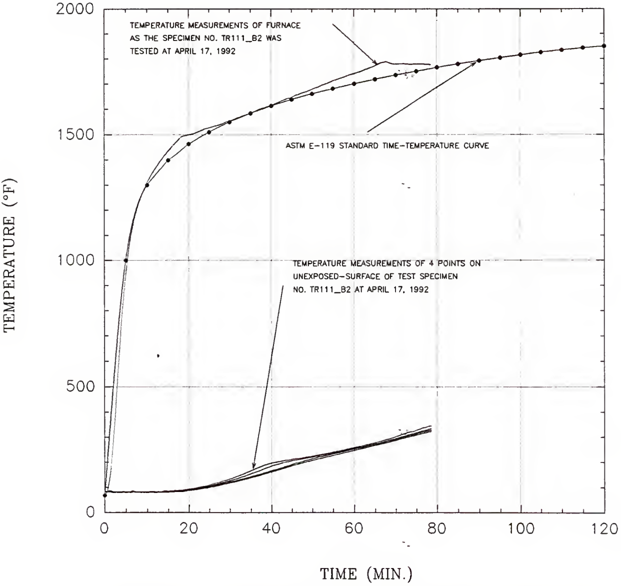

FIGURE C-5: FIRING DATA OF SPECIMEN NO. TR111_B2

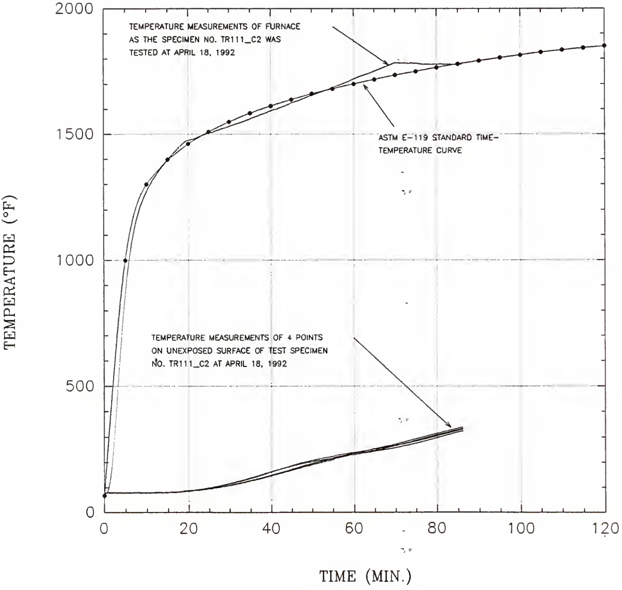

FIGURE C-6: FIRING DATA OF SPECIMEN NO. TR111_C2

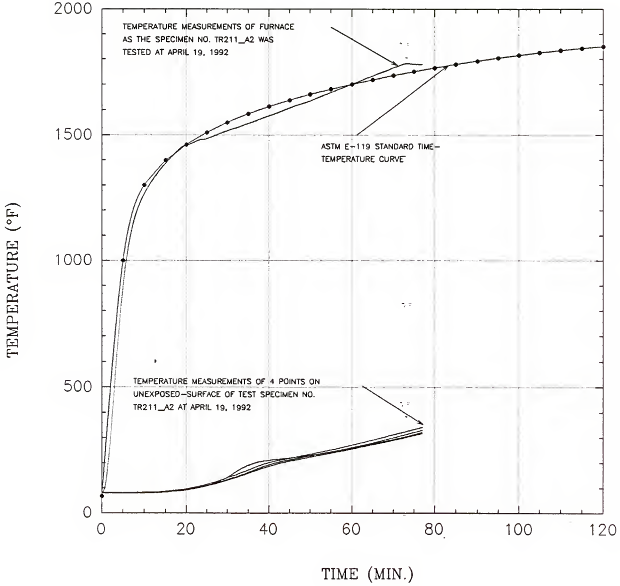

FIGURE C-7: FIRING DATA OF SPECIMEN NO. TR211_A2

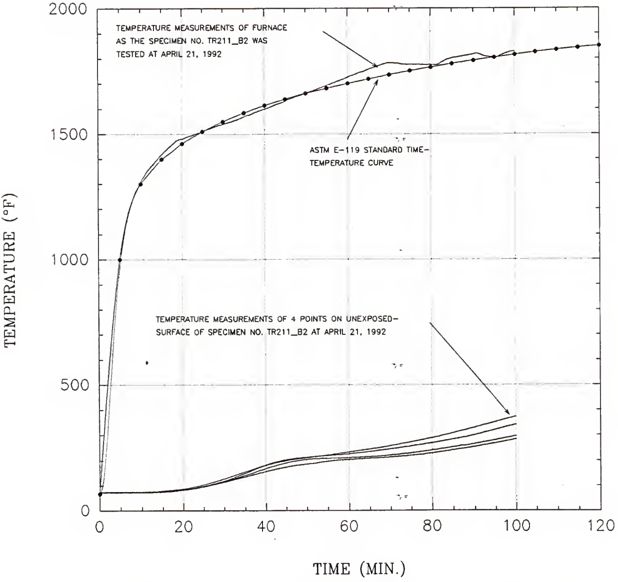

FIGURE C-8: FIRING DATA OF SPECIMEN NO. TR 211_B2

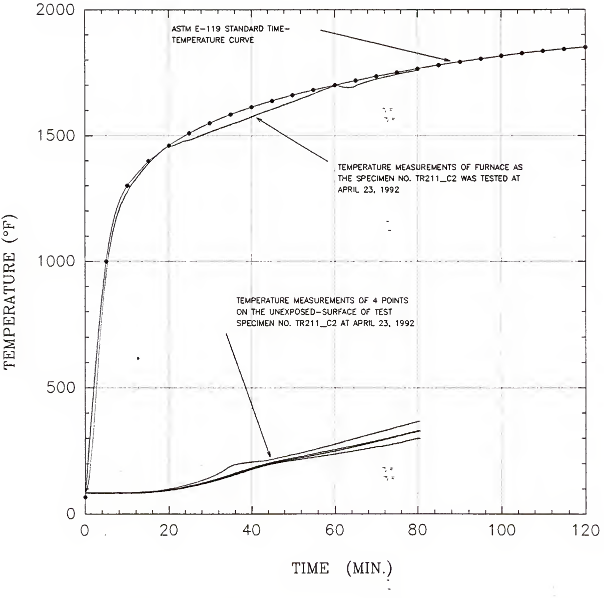

FIGURE C-9: FIRING DATA OF SPECIMEN NO. TR211_C2

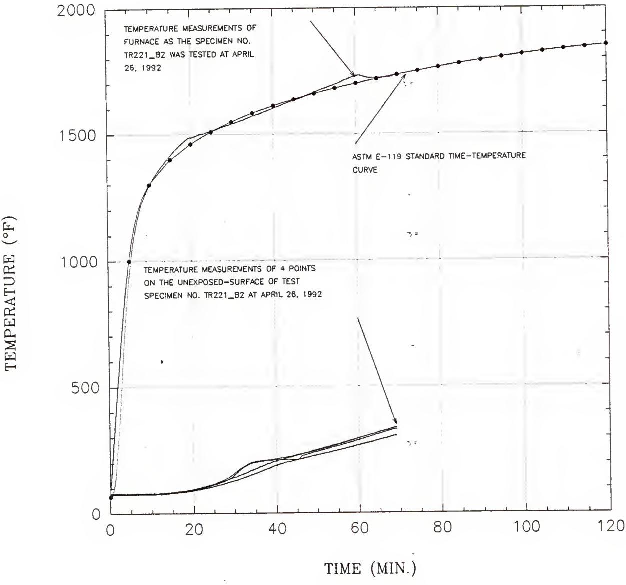

FIGURE C-10: FIRING DATA OF SPECIMEN NO. TR221_B2

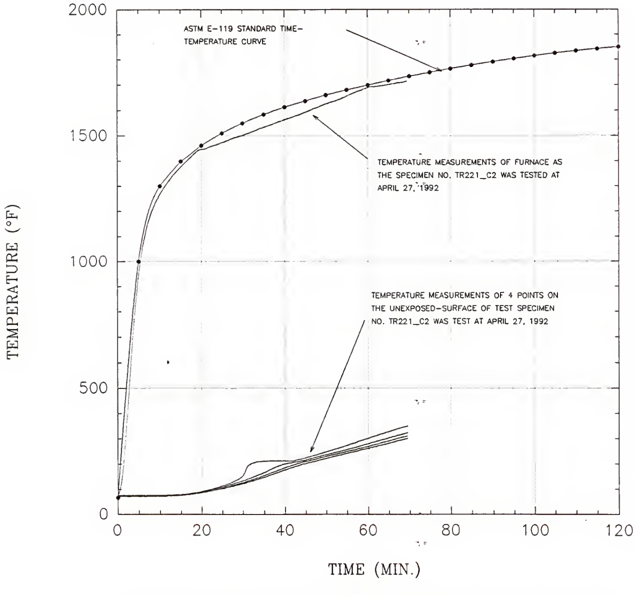

FIGURE C-11: FIRING DATA OF SPECIMEN NO. TR221_C2

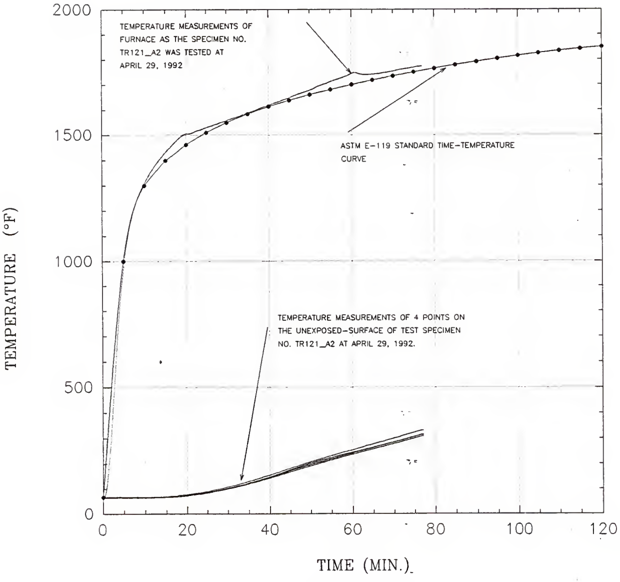

FIGURE C-12: FIRING DATA OF SPECIMEN NO. TR121_A2

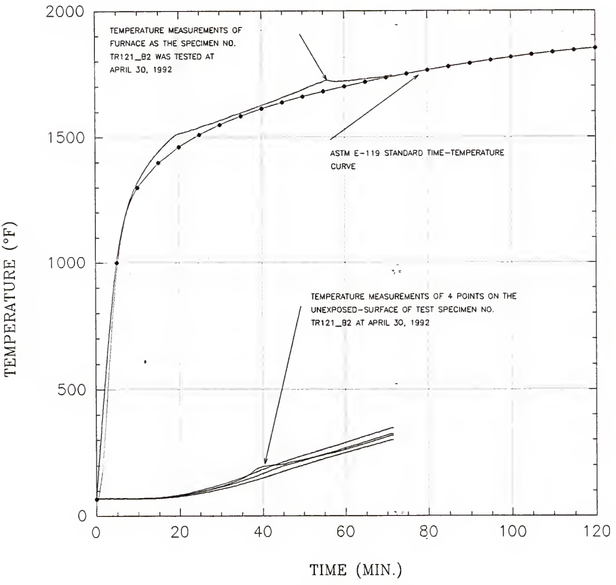

FIGURE C-13: FIRING DATA OF SPECIMEN NO. TR121_B2

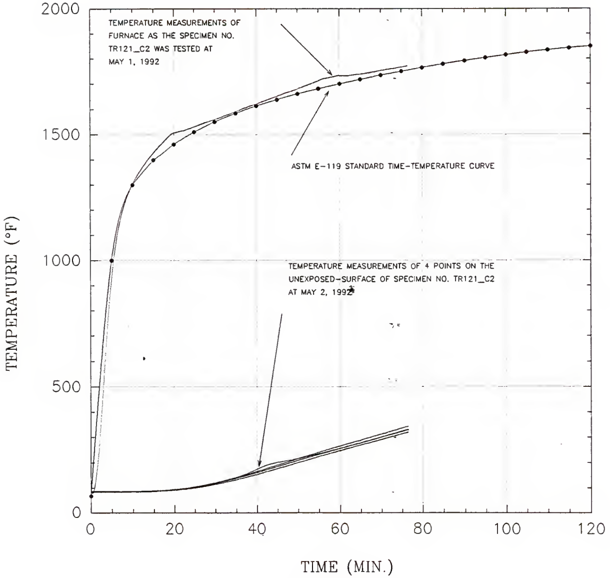

FIGURE C-14: FIRING DATA OF SPECIMEN NO. TR121_C2

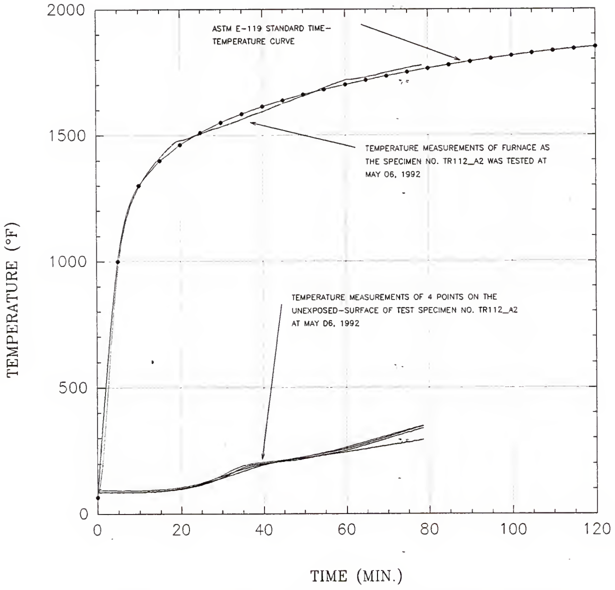

FIGURE C-15: FIRING DATA OF SPECIMEN NO. TR112_A2

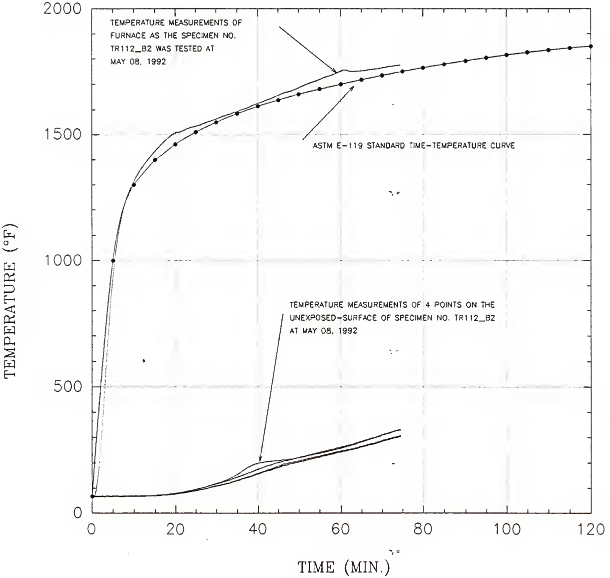

FIGURE C-16: FIRING DATA OF SPECIMEN NO. TR112_B2

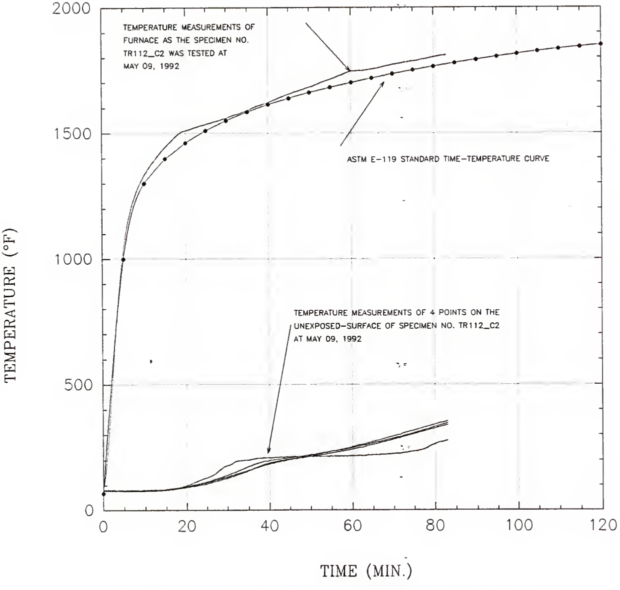

FIGURE C-17: FIRING DATA OF SPECIMEN NO. TR112_C2

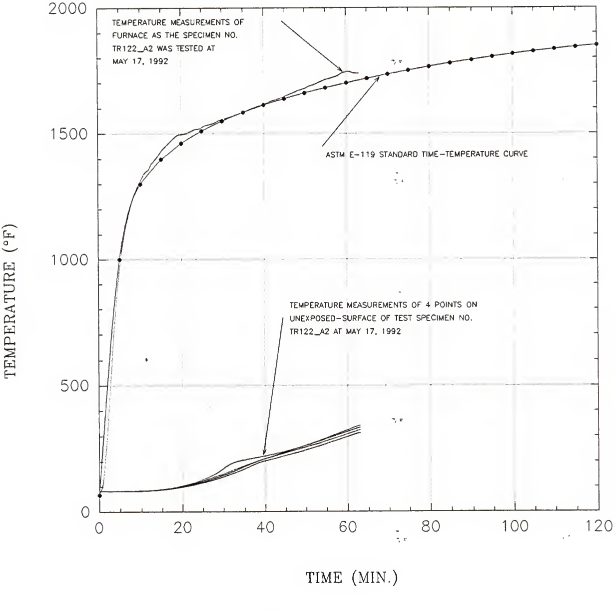

FIGURE C-18: FIRING DATA OF SPECIMEN NO. TR122_A2

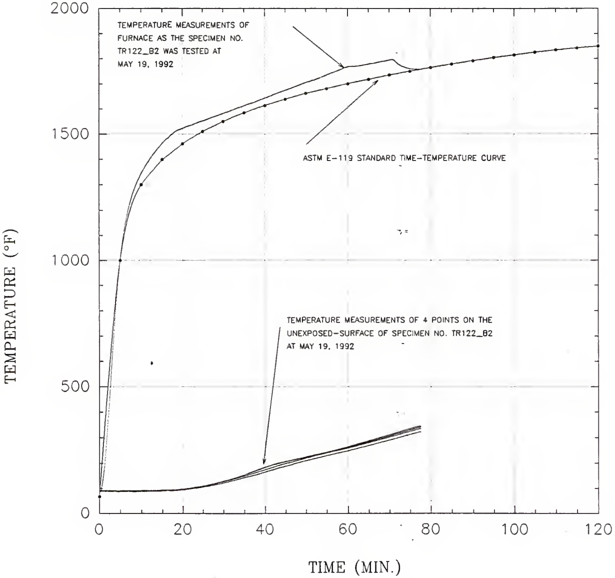

FIGURE C-19: FIRING DATA OF SPECIMEN NO. TR122_B2

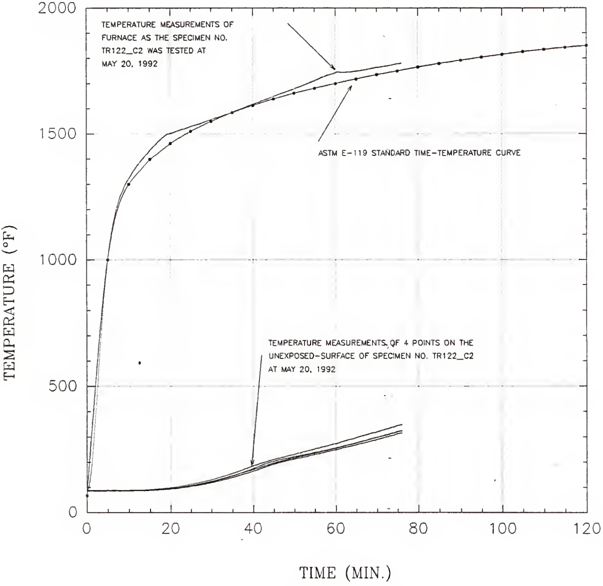

FIGURE C-20: FIRING DATA OF SPECIMEN NO. TR122_C2

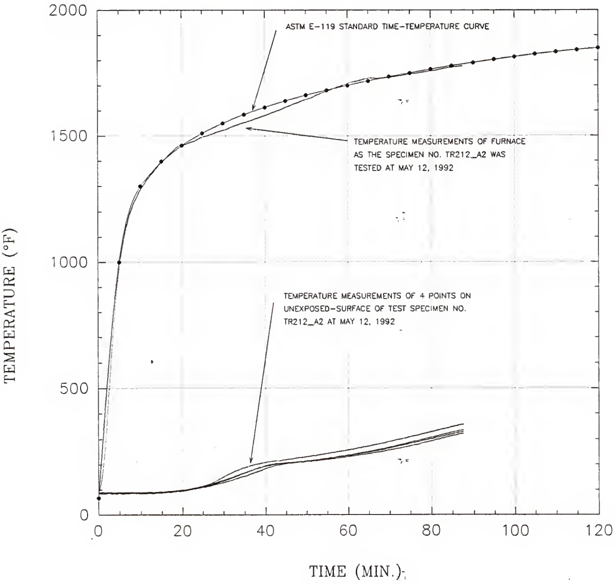

FIGURE C-21: FIRING DATA OF SPECIMEN NO. TR212_A2

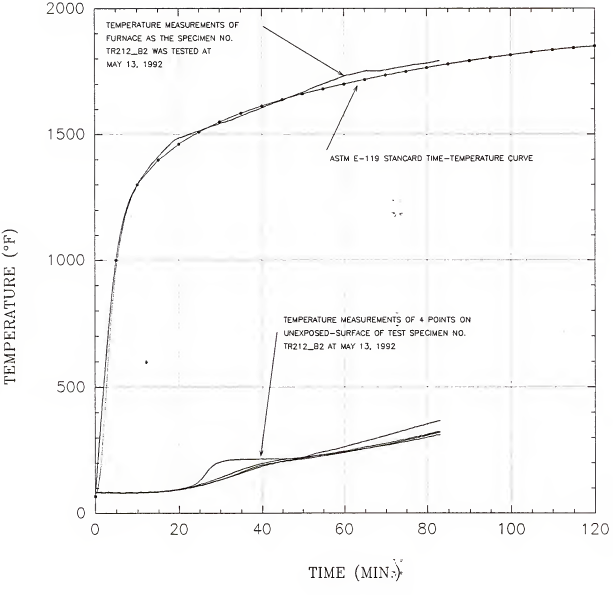

FIGURE C-22: FIRING DATA OF SPECIMEN NO. TR212_B2

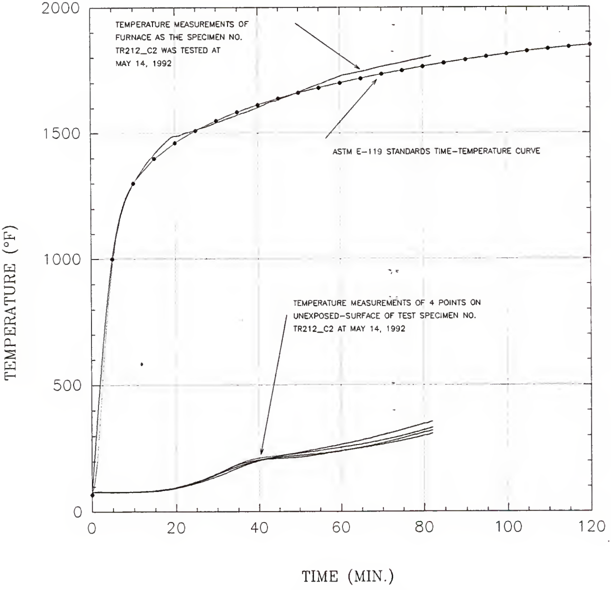

FIGURE C-23: FIRING DATA OF SPECIMEN NO. TR212)C2

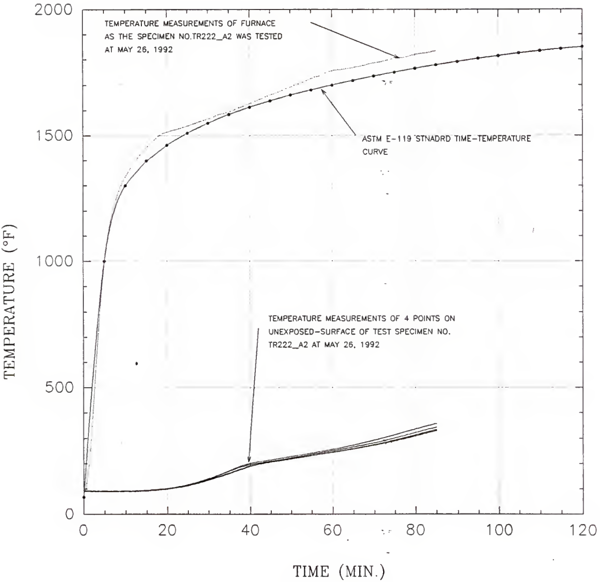

FIGURE C-24: FIRING DATA OF SPECIMEN NO. TR222_A2

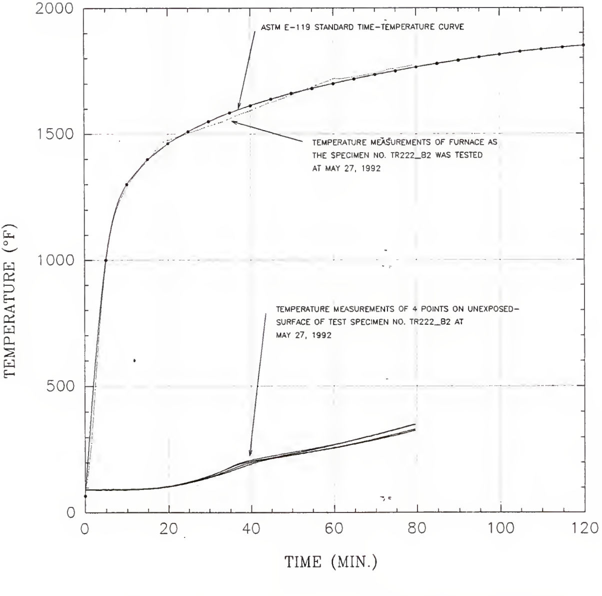

FIGURE C-25: FIRING DATA OF SPECIMEN NO. TR222_B2

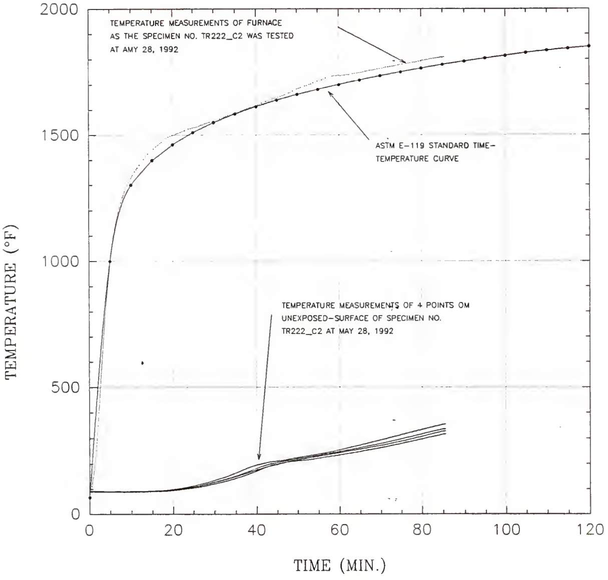

FIGURE C-26: FIRING DATA OF SPECIMEN NO. TR222_C2

APPENDIX D
SUMMARY OF TEST DATA ON SCHMIDT REBOUND HAMMER TEST, ULTRASONIC PULSE VELOCITY TEST, AND COMPRESSIVE STRENGTH OF DRILLED CORES

	A	B	C	D	E	F	G	H	I	J	K	L
1	# of	# of	Schedmit Hammer			Ultrasonic Pulse Velocity			Compressive	Percentage Loss	Percentage Loss	Percentage Loss
2	Test Specimen	Test	Rebound Number				Test		Strength	of Rebound Number	of Rebound Number	of Pulse Velociy
3		Location		(R)		(Trabsit Time, us)			of Drilled Core	between 1st and	between 1st and	between 1st and
4			Pre-1st	Pre-2nd	After	Pre-1st	Pre-2nd	After	(psi)	2nd Measurement	3rd Measurement	2nd Measurement
5			Firing	Firing	2nd	Firing	Firing	2nd		at Each Test	at Each Test	at Each Test
6					Firing			Firing		Point	Point	Point
7	TR000 - A	#1	36.2	28.2		26.2	52.5			-22.10%		-50.10%
8		#2	35.9	30.2		26	53.4		728.21	-15.88%		-51.31%
9		#3	36.2	36		25.7	54.4			-0.55%		-52.76%
10		#4	40.2	29.6		24.9	52.7		878.55	-26.37%		-52.75%
11		#5	34.3	33.9		25.8	53.4			-1.17%		-51.69%
12		#6	37.8	35.8		26.3	61.6		964.12	-5.29%		-57.31%
13		#7	38.9	28.2		25.9	56.5		796.77	-27.51%		-54.16%
14	TR000 - B	#1	35.5	34		25.2	52.4			-4.23%		-51.91%
15		#2	33	32		25.7	55.5		946.67	-3.03%		-53.69%
16		#3	35.8	35		26	54.5			-2.23%		-52.29%
17		#4	34.8	30		24.9	54.4		1128.73	-13.79%		-54.23%
18		#5	38.6	33		25.6	61.3			-14.51%		-58.24%
19		#6	34.2	29.5		25.6	60.1		1274.36	-13.74%		-57.40%
20		#7	34	31		24.8	59.5		1058.17	-8.82%		-58.32%
21	TR000 - C	#1	35.8	34		24.8	55.4			-5.03%		-55.23%
22		#2	37.3	31.9		23.9	54.7		1607.38	-14.48%		-56.31%
23		#3	34.2	28.8		24.8	58.1			-15.79%		-57.31%
24		#4	34.2	29.6		25.3	48.2		1019.50	-13.45%		-47.51%
25		#5	36.6	31.5		25.3	53			-13.93%		-52.26%
26		#6	34	28.3		24.9	43		1529.24	-16.76%		-42.09%
27		#7	40.2	28.1		25.1	45		2548.74	-30.10%		-44.22%
28	TR111 - A	#1	35.9	31.4	33	25.8	37.9	52.2	2168.13	-12.53%	-8.08%	-31.93%
29		#2	37.8	31.4	30.5	25.6	38.9	51	1053.84	-16.93%	-19.31%	-34.19%
30		#3	39.2	34	28	25.5	35.3	45.8	1858.40	-13.27%	-28.57%	-27.76%
31		#4	37.2	32.2	33	25.9	36.2	57.5	2388.58	-13.44%	-11.29%	-28.45%

	A	B	C	D	E	F	G	H	I	J	K	L
32		#5	35.4	29.9	26	25.6	37.5	54.7	2277.25	-15.54%	-26.55%	-31.73%
33		#6	35	29.9	24.5	25.5	36.9	51.4	1951.31	-14.57%	-30.00%	-30.89%
34		#7	37.6	28.6	26	24.8	39.6	58.1	1247.81	-23.94%	-30.85%	-37.37%
35	TR111 - B	#1	45	38.4	26	24.8	35.8	48.3	1367.70	-14.67%	-42.22%	-30.73%
36		#2	45.9	39.2	28.5	24.8	37.5	48	1333.75	-14.60%	-37.91%	-33.87%
37		#3	40.1	35.8	30	24.7	33.8	42.8	2455.63	-10.72%	-25.19%	-26.92%
38		#4	41.5	38.4	33.5	24.8	37.9	47.2	2331.30	-7.47%	-19.28%	-34.56%
39		#5	38.8	29.8	32.5	24.6	34.2	41.2	2570.78	-23.20%	-16.24%	-28.07%
40		#6	34.2	31.6	25	24.9	34.7	42.2	2797.56	-7.60%	-26.90%	-28.24%
41		#7	34.4	32.6	29	24.7	34.9	43.7	2199.10	-5.23%	-15.70%	-29.23%
42	TR111 - C	#1	33.8	34.4	27.8	24.1	33.6	47.6	2963.55	1.78%	-17.75%	-28.27%
43		#2	33.6	28.2	24.2	25.2	36.9	53.4	1721.89	-16.07%	-27.98%	-31.71%
44		#3	29.2	29.6	32	25.1	32.9	42.1	2663.69	1.37%	9.59%	-23.71%
45		#4	34.8	31	27.6	25.5	38.5	51.5	1554.20	-10.92%	-20.69%	-33.77%
46		#5	35	30.2	33.6	24.8	34.7	43.7	1212.27	-13.71%	-4.00%	-28.53%
47		#6	34.8	31.6	29	26.3	38.8	49.7	1517.69	-9.20%	-16.67%	-32.22%
48		#7	32.2	26.2	30.4	24.3	36.3	49.7	2079.66	-18.63%	-5.59%	-33.06%
49	TR121 - A	#1	31.6	32	29.5	24.4	37.9	48.4	882.86	1.27%	-6.65%	-35.62%
50		#2	30.2	38	36.5	26	39.3	51.9	2297.30	25.83%	20.86%	-33.84%
51		#3	36	29.5	28	25.6	34.4	40.6	820.46	-18.06%	-22.22%	-25.58%
52		#4	32.4	33	29.5	25.8	38.2	46.5	1667.62	1.85%	-8.95%	-32.46%
53		#5	33.4	33	30	25.4	36	46.5	2652.46	-1.20%	-10.18%	-29.44%
54		#6	34.8	33	29.5	26.3	36.8	44.8	2810.16	-5.17%	-15.23%	-28.53%
55		#7	33.2	33	29.5	26.7	41.9	53	1119.94	-0.60%	-11.14%	-36.28%
56	TR121 - B	#1	32.4	32.5	31.2	25.2	37.8	41.8	1509.66	0.31%	-3.70%	-33.33%
57		#2	38.2	28.5	30.8	26.8	41.3	55.7	2060.00	-25.39%	-19.37%	-35.11%
58		#3	31	30.5	23.6	24.1	34.1	42.3	1798.41	-1.61%	-23.87%	-29.33%
59		#4	32.4	30.5	32.8	25.9	41.3	49.6	982.39	-5.86%	1.23%	-37.29%
60		#5	33.8	32	30.2	24.1	32.3	41.6	2362.94	-5.33%	-10.65%	-25.39%
61		#6	31.2	28	29.8	25.1	39.4	49.4	1487.73	-10.26%	-4.49%	-36.29%
62		#7	35	33	30.6	27.5	40.6	51.4	2180.96	-5.71%	-12.57%	-32.27%

	A	B	C	D	E	F	G	H	I	J	K	L
63	TR121 - C	#1	41	36.6	32.4	24.8	38	45.6	1628.95	-10.73%	-20.98%	-34.74%
64		#2	42	33	33.8	25.1	39.8	45.7	1791.85	-21.43%	-19.52%	-36.93%
65		#3	37	36	35	25.5	37.9	45.5	1134.45	-2.70%	-5.41%	-32.72%
66		#4	41.5	35	35.4	25.8	41.6	53.8	1140.27	-15.66%	-14.70%	-37.98%
67		#5	41	36.8	37.8	25.6	37.6	45.4	1759.26	-10.24%	-7.80%	-31.91%
68		#6	36	31.4	33.4	25.6	38.5	46.5	978.80	-12.78%	-7.22%	-33.51%
69		#7	36.5	32.6	30.2	24.5	41.4	52.1	1368.32	-10.68%	-17.26%	-40.82%
70	TR112 - A	#1	39.2	33.6	32.4	25.2	35.6	51.8	1791.85	-14.29%	-17.35%	-29.21%
71		#2	36.8	36	29.8	25.3	36.6	51.5	1205.43	-2.17%	-19.02%	-30.87%
72		#3	34.3	28.4	31.6	24.9	31.9	34.3	1847.54	-17.20%	-7.87%	-21.94%
73		#4	34	30.2	27.4	25.9	39.4	48.2	2009.59	-11.18%	-19.41%	-34.26%
74		#5	34.6	38.4	33.2	25.3	35.5	49.2	2443.42	10.98%	-4.05%	-28.73%
75		#6	34.8	31.2	24.4	24.5	33.9	45.9	1431.38	-10.34%	-29.89%	-27.73%
76		#7	32.6	30.6	29.6	24.7	37.4	56.8	1205.43	-6.13%	-9.20%	-33.96%
77	TR112 - B	#1	33.8	29.6	28.2	25.7	35.2	43.7	2606.32	-12.43%	-16.57%	-26.99%
78		#2	38.2	31.8	27.6	25.7	39.7	45	1726.69	-16.75%	-27.75%	-35.26%
79		#3	41	34	28	26.2	33.9	41.2	3257.90	-17.07%	-31.71%	-22.71%
80		#4	40.2	32.6	30.8	25.6	40.1	48.2	1201.03	-18.91%	-23.38%	-36.16%
81		#5	37.2	30.2	35.8	25.4	36.8	45.8	1498.63	-18.82%	-3.76%	-30.98%
82		#6	40.8	29.4	28.2	26.9	38.6	48.7	1924.97	-27.94%	-30.88%	-30.31%
83		#7	37.8	35.6	26.2	26.4	38	53.2	2052.47	-5.82%	-30.69%	-30.53%
84	TR112 - C	#1	37	33	29	25.4	30.9	Exposed	2174.83	-10.81%	-21.62%	-17.80%
85		#2	36.5	36	25.5	25.2	31	surface	1912.36	-1.37%	-30.14%	-18.71%
86		#3	38	36.2	29	24.9	31.3	was too	2606.31	-4.74%	-23.68%	-20.45%
87		#4	34	30.4	27.5	25.1	31.3	fragile to	1368.31	-10.59%	-19.12%	-19.81%
88		#5	36.5	38.4	32.5	24.8	30	apply the	2345.68	5.21%	-10.96%	-17.33%
89		#6	35	30.6	28.5	25	30.2	ransduce	2280.53	-12.57%	-18.57%	-17.22%
90		#7	34	32.8	25	25.3	33.5		1558.09	-3.53%	-26.47%	-24.48%
91	TR122 - A	#1	33	30.2	28.8	25.9	34	42.2	1844.84	-8.48%	-12.73%	-23.82%
92		#2	34	29.6	30.4	26	34.2	44.3	2528.20	-12.94%	-10.59%	-23.98%
93		#3	35.5	27.6	29	25.4	32.4	44.6	2019.90	-22.25%	-18.31%	-21.60%

	A	B	C	D	E	F	G	H	I	J	K	L
94		#4	34.5	26.8	25	25	29.5	35.5	2019.90	-22.32%	-27.54%	-15.25%
95		#5	36	25.8	25.4	25.5	31.7	40.8	1298.41	-28.33%	-29.44%	-19.56%
96		#6	35.5	28.8	22.2	25.9	33.6	41.5	2182.79	-18.87%	-37.46%	-22.92%
97		#7	35	26.6	19.2	25.8	32.3	40	2622.57	-24.00%	-45.14%	-20.12%
98	TR122 - B	#1	34.5	30.8	26.4	25.7	34.2	49.8	1107.69	-10.72%	-23.48%	-24.85%
99		#2	36	32	25.4	26.2	35.8	46.4	1107.69	-11.11%	-29.44%	-26.82%
100		#3	35.5	31.2	27.4	25.6	31.8	41.9	2215.37	-12.11%	-22.82%	-19.50%
101		#4	36.5	30.4	29.8	26.5	36.3	53	973.80	-16.71%	-18.36%	-27.00%
102		#5	35	29.8	34.2	25.7	34.9	46.3	1726.69	-14.86%	-2.29%	-26.36%
103		#6	37.5	32.2	28	25.9	35.8	52.4	1657.89	-14.13%	-25.33%	-27.65%
104		#7	33	29	28	26.2	39	49.6	1957.60	-12.12%	-15.15%	-32.82%
105	TR122 - C	#1	45	38	31.5	24.8	30.4	38.7	1628.95	-15.56%	-30.00%	-18.42%
106		#2	44.6	38	30	25.3	33.9	45.5	1791.85	-14.80%	-32.74%	-25.37%
107		#3	42.5	40	33.5	25.9	34.9	39.7	1134.45	-5.88%	-21.18%	-25.79%
108		#4	41.4	39.2	29	26.4	36	46.5	1140.27	-5.31%	-29.95%	-26.67%
109		#5	39.2	34.4	30.5	25.5	34	38.6	1759.26	-12.24%	-22.19%	-25.00%
110		#6	41.8	36.2	28	26.6	40.6	47	978.80	-13.40%	-33.01%	-34.48%
111		#7	43.4	39	32.5	25.8	37.8	52.4	1368.32	-10.14%	-25.12%	-31.75%
112	TR221 - A	#1										
113		#2										
114		#3										
115		#4	Specimen was broken after first firing									
116		#5										
117		#6										
118		#7										
119	TR221 - B	#1	33.3	28.5	26	23.9	29.3	39.2	1712.84	-14.41%	-21.92%	-18.43%
120		#2	33.9	30.5	32	23.5	30.8	39.6	1785.28	-10.03%	-5.60%	-23.70%
121		#3	34.3	25	29.5	23.8	26.8	37.2	1772.20	-27.11%	-13.99%	-11.19%
122		#4	34.1	30	28	23.8	29.7	40.3	1745.79	-12.02%	-17.89%	-19.87%
123		#5	34.9	33	35.5	23.8	27.5	38.8	3293.94	-5.44%	1.72%	-13.45%
124		#6	35.1	39.5	31.5	24.6	30.4	40.3	1247.10	12.54%	-10.26%	-19.08%

	A	B	C	D	E	F	G	H	I	J	K	L
125		#7	28.5	30	36.5	24.3	31.3	40.5	2464.62	5.26%	28.07%	-22.36%
126	TR221 - C	#1	37	32	30.5	24.8	30.2	43.9	2812.07	-13.51%	-17.57%	-17.88%
127		#2	33	27	28	23.8	28.7	43.8	1903.47	-18.18%	-15.15%	-17.07%
128		#3	34.5	36.5	29	24.3	29.6	40.5	2133.21	5.80%	-15.94%	-17.91%
129		#4	35	29	29.5	23.9	29	40	1279.92	-17.14%	-15.71%	-17.59%
130		#5	38	36.5	27	26.5	31.4	44.1	1476.83	-3.95%	-28.95%	-15.61%
131		#6	33.8	30	24	24.2	30.2	45.1	1969.11	-11.24%	-28.99%	-19.87%
132		#7	36.5	38.5	31	24.2	30.4	42.7	1833.80	5.48%	-15.07%	-20.39%
133	TR212 - A	#1	33	30	29.5	24.3	30.7	45.7	1628.95	-9.09%	-10.61%	-20.85%
134		#2	35.5	30.5	33.5	24.3	30.4	47	2321.59	-14.08%	-5.63%	-20.07%
135		#3	37	30.5	28.5	24.5	33.6	48.6	1298.40	-17.57%	-22.97%	-27.08%
136		#4	38.5	26	20	24.9	30.4	45.3	1102.03	-32.47%	-48.05%	-18.09%
137		#5	33.5	30.5	30.5	24.3	30.3	44.4	2044.98	-8.96%	-8.96%	-19.80%
138		#6	37	30	24.5	24.9	33.6	52.4	1628.95	-18.92%	-33.78%	-25.89%
139		#7	36	27	28.5	24.6	35.5	57.8	1498.63	-25.00%	-20.83%	-30.70%
140	TR212 - B	#1	35	34	29.5	24.9	30.2	45.4	1785.31	-2.86%	-15.71%	-17.55%
141		#2	34.5	34	25	24.9	30.5	46.2	2280.53	-1.45%	-27.54%	-18.36%
142		#3	35.5	31	26	24.6	28.1	39.8	1954.74	-12.68%	-26.76%	-12.46%
143		#4	35.5	31	28	24.7	29.4	45.9	1661.52	-12.68%	-21.13%	-15.99%
144		#5	36.5	31	30.5	25.3	28.8	41.7	2106.84	-15.07%	-16.44%	-12.15%
145		#6	34	31	27.5	25.6	30.5	46	1433.47	-8.82%	-19.12%	-16.07%
146		#7	35	32	24.5	26	32.3	46.3	1912.36	-8.57%	-30.00%	-19.50%
147	TR212 - C	#1	31	31	22.4	23.9	27.4	Exposed	1238.00	0.00%	-27.74%	-12.77%
148		#2	33	30	19.8	24.2	30.4	surface	2402.05	-9.09%	-40.00%	-20.39%
149		#3	33.5	30	25.4	23.9	28.7	was too	2600.61	-10.45%	-24.18%	-16.72%
150		#4	34.5	30.5	25.2	24.4	29.3	fragile to	1498.63	-11.59%	-26.96%	-16.72%
151		#5	33	34	22.6	24.3	26.7	apply the	1954.74	3.03%	-31.52%	-8.99%
152		#6	33.5	30	29.2	24.3	27.4	ransduce	1987.32	-10.45%	-12.84%	-11.31%
153		#7	34.5	32	22	24.4	29.1		1628.95	-7.25%	-36.23%	-16.15%
154	TR222 - A	#1	34.2	34.8	33.4	23.7	30	45.2	1403.94	1.75%	-2.34%	-21.00%
155		#2	39.8	36.8	32.2	23.7	32.5	50.8	2052.48	-7.54%	-19.10%	-27.08%

	A	B	C	D	E	F	G	H	I	J	K	L
156		#3	38	34	34.2	24	29.2	41.5	1954.74	-10.53%	-10.00%	-17.81%
157		#4	30.2	31.4	27.6	23.8	30.4	43.3	1205.43	3.97%	-8.61%	-21.71%
158		#5	37.2	34	32.4	23.8	30.7	43.3	1694.11	-8.60%	-12.90%	-22.48%
159		#6	35.9	34.4	30.2	23.8	30.9	49.1	1922.16	-4.18%	-15.88%	-22.98%
160		#7	39	36	30.4	24.2	34.1	45.4	1365.32	-7.69%	-22.05%	-29.03%
161	TR222 - B	#1	39.8	37.6	30.2	25.8	30.3	42.9	1828.43	-5.53%	-24.12%	-14.85%
162		#2	38.8	37.4	30	25.3	32.9	45.9	1634.92	-3.61%	-22.68%	-23.10%
163		#3	39.8	37.6	38	25.4	30.1	53.4	2612.05	-5.53%	-4.52%	-15.61%
164		#4	35.7	37.4	36	25.8	30.1	45.4	3262.69	4.76%	0.84%	-14.29%
165		#5	34	35.8	39.4	25.6	28.8	38.3	2767.19	5.29%	15.88%	-11.11%
166		#6	36	36	32.8	24.9	30.7	43.6	1954.74	0.00%	-8.89%	-18.89%
167		#7	37	35	30.4	25.3	32.6	47.8	2313.11	-5.41%	-17.84%	-22.39%
168	TR222 - C	#1	34	34.8	32.4	27.6	34.1	53.4	2171.66	2.35%	-4.71%	-19.06%
169		#2	37.3	39.2	27.6	26	35.2	53.9	1625.38	5.09%	-26.01%	-26.14%
170		#3	38.1	37.4	34.2	25.8	32.8	53.7	2638.90	-1.84%	-10.24%	-21.34%
171		#4	36.8	34	31.4	25.8	33.8	51.4	1533.46	-7.61%	-14.67%	-23.67%
172		#5	37	33.6	32.2	25.4	32.1	48.8	814.47	-9.19%	-12.97%	-20.87%
173		#6	35.5	34.2	32	27.2	31.3	50.7	1561.51	-3.66%	-9.86%	-13.10%
174		#7	38.4	33.6	30	28.2	33.9	56.2	928.50	-12.50%	-21.88%	-16.81%
175	TR211 - A	#1	33.9	30.4	29.8	23.6	29.6	44.9	2158.10	-10.32%	-12.09%	-20.27%
176		#2	35.9	32.8	30.2	25.4	34.2	54.5	1592.77	-8.64%	-15.88%	-25.73%
177		#3	34.4	32.4	30.6	23.2	29.4	42.8	1536.83	-5.81%	-11.05%	-21.09%
178		#4	34.8	30.4	23.4	24.1	32.3	47.5	799.33	-12.64%	-32.76%	-25.39%
179		#5	36	30.6	28.4	23.7	27.3	42	1997.53	-15.00%	-21.11%	-13.19%
180		#6	34	31.8	29.8	25.1	32.8	52.1	1602.23	-6.47%	-12.35%	-23.48%
181		#7	39	30.2	32	23.8	31.8	53	1054.06	-22.56%	-17.95%	-25.16%
182	TR211 - B	#1	32.2	30.4	29.8	25.3	32.3	Exposed	1608.10	-5.59%	-7.45%	-21.67%
183		#2	34.6	27	25.5	26.3	32.5	surface	1225.96	-21.97%	-26.30%	-19.08%
184		#3	34.2	33.4	25.8	25.4	28.5	was too	2338.69	-2.34%	-24.56%	-10.88%
185		#4	32.8	29.2	28	26.4	31.4	fragile to	1692.33	-10.98%	-14.63%	-15.92%
186		#5	33.8	37.2	25	24.2	28.9	apply the	1619.98	10.06%	-26.04%	-16.26%

	A	B	C	D	E	F	G	H	I	J	K	L
187		#6	36.6	35.2	27.5	25.7	33.6	ransduce	1870.66	-3.83%	-24.86%	-23.51%
188		#7	36.4	30.4	30	25.1	35.5		1444.02	-16.48%	-17.58%	-29.30%
189	TR211 - C	#1	34.6	32.5	26.5	25.4	37.3	55	1312.75	-6.07%	-23.41%	-31.90%
190		#2	34.2	27.5	23.5	24.6	31.9	44.6	1032.48	-19.59%	-31.29%	-22.88%
191		#3	37.4	34.5	28	23.8	30.1	40.8	1312.75	-7.75%	-25.13%	-20.93%
192		#4	35.4	29	27.8	23.2	30.4	46	1990.97	-18.08%	-21.47%	-23.68%
193		#5	34.2	34.5	25	24.7	29.8	42.5	1119.94	0.88%	-26.90%	-17.11%
194		#6	36.3	30	26.5	24.1	33.3	47.4	1575.29	-17.36%	-27.00%	-27.63%
195		#7	32.9	37	29	24.8	34.6	54	850.16	12.46%	-11.85%	-28.32%

	M	N	O	P	Q	R	S
1	Percentage Loss	Percentage	Seven-Point	Seven-Point	Seven-Point	Seven-Point	Average
2	of Pulse Velocity	Loss of	Average Percentage	Average Percentage	Average Percentage	Average Percentage	Percentage
3	between 1st and	Compressive	Loss of Rebound	Loss of Rebound	Loss of Pulse Velocity	Loss of Pulse Velocity	Loss of
4	3rd Measurement	Strength of	Number between 1rst	Number between 1rst	between 1st and 2nd	between 1st and 3rd	Compressive
5	at Each Test	Each Test	and 2nd Mesasurement	and 3rd Measurement	Measurement of	Measurement of	Strength of
6	Point	Point	of Each Specimen	of Each Specimen	Each Specimen	Each Specimen	Each Specimen
7			-14.12%		-52.87%	#DIV/0!	-77.83%
8		-80.82%					
9							
10		-76.86%					
11							
12		-74.61%					
13		-79.02%					
14			-8.62%		-55.16%	#DIV/0!	-70.98%
15		-75.07%					
16							
17		-70.28%					
18							
19		-66.44%					
20		-72.13%					
21			-15.65%		-50.71%	#DIV/0!	-55.86%
22		-57.67%					
23							
24		-73.15%					
25							
26		-59.73%					
27		-32.88%					
28	-50.57%	-42.90%	-15.75%	-22.09%	-31.76%	-51.51%	-51.30%
29	-49.80%	-72.25%					
30	-44.32%	-51.06%					
31	-54.96%	-37.10%					

	M	N	O	P	Q	R	S
32	-53.20%	-40.03%					
33	-50.39%	-48.61%					
34	-57.31%	-67.14%					
35	-48.65%	-63.98%	-11.93%	-26.20%	-30.23%	-44.50%	-43.36%
36	-48.33%	-64.88%					
37	-42.29%	-35.33%					
38	-47.46%	-38.61%					
39	-40.29%	-32.30%					
40	-41.00%	-26.33%					
41	-43.48%	-42.09%					
42	-49.37%	-21.96%	-9.34%	-11.87%	-30.18%	-47.78%	-48.41%
43	-52.81%	-54.66%					
44	-40.38%	-29.85%					
45	-50.49%	-59.07%					
46	-43.25%	-68.08%					
47	-47.08%	-60.03%					
48	-51.11%	-45.23%					
49	-49.59%	-76.75%	0.56%	-7.64%	-31.68%	-45.32%	-53.91%
50	-49.90%	-39.50%					
51	-36.95%	-78.39%					
52	-44.52%	-56.08%					
53	-45.38%	-30.15%					
54	-41.29%	-26.00%					
55	-49.62%	-70.51%					
56	-39.71%	-60.24%	-7.69%	-10.49%	-32.71%	-45.74%	-53.42%
67	-51.89%	-45.75%					
58	-43.03%	-52.64%					
59	-47.78%	-74.13%					
60	-42.07%	-37.77%					
61	-49.19%	-60.82%					
62	-46.50%	-42.57%					

	M	N	O	P	Q	R	S
63	-45.61%	-57.10%	-12.03%	-13.27%	-35.52%	-46.89%	-63.13%
64	-45.08%	-52.81%					
65	-43.96%	-70.13%					
66	-52.04%	-69.97%					
67	-43.61%	-53.67%					
68	-44.95%	-74.22%					
69	-52.98%	-63.97%					
70	-51.35%	-52.81%	-7.19%	-15.26%	-29.53%	-46.80%	-55.10%
71	-50.87%	-68.26%					
72	-27.41%	-51.35%					
73	-46.27%	-47.08%					
74	-48.58%	-35.65%					
75	-46.62%	-62.31%					
76	-56.51%	-68.26%					
77	-41.19%	-31.36%	-16.82%	-23.53%	-30.42%	-43.87%	-46.32%
78	-42.89%	-54.53%					
79	-36.41%	-14.21%					
80	-46.89%	-68.37%					
81	-44.54%	-60.53%					
82	-44.76%	-49.31%					
83	-50.38%	-45.95%					
84		-42.73%	-5.49%	-21.51%	-19.40%	#DIV/0!	-46.41%
85		-49.64%					
86		-31.37%					
87		-63.97%					
88		-38.23%					
89		-39.94%					
90		-58.97%					
91	-38.63%	-51.42%	-19.60%	-25.89%	-21.04%	-37.59%	-45.39%
92	-41.31%	-33.42%					
93	-43.05%	-46.81%					

	M	N	O	P	Q	R	S
94	-29.58%	-46.81%					
95	-37.50%	-65.81%					
96	-37.59%	-42.52%					
97	-35.50%	-30.94%					
98	-48.39%	-70.83%	-13.11%	-19.55%	-26.43%	-46.15%	-59.57%
99	-43.53%	-70.83%					
100	-38.90%	-41.66%					
101	-50.00%	-74.36%					
102	-44.49%	-54.53%					
103	-50.57%	-56.34%					
104	-47.18%	-48.45%					
105	-35.92%	-57.10%	-11.05%	-27.74%	-26.78%	-40.91%	-63.13%
106	-44.40%	-52.81%					
107	-34.76%	-70.13%					
108	-43.23%	-69.97%					
109	-33.94%	-53.67%					
110	-43.40%	-74.22%					
111	-50.76%	-63.97%					
112							
113							
114							
115							
116							
117							
118							
119	-39.03%	-54.89%	-7.32%	-5.70%	-18.30%	-39.18%	-47.25%
120	-40.66%	-52.99%					
121	-36.02%	-53.33%					
122	-40.94%	-54.03%					
123	-38.66%	-13.26%					
124	-38.96%	-67.16%					

	M	N	O	P	Q	R	S
125	-40.00%	-35.10%					
126	-43.51%	-25.95%	-7.54%	-19.63%	-18.04%	-42.71%	-49.56%
127	-45.66%	-49.87%					
128	-40.00%	-43.82%					
129	-40.25%	-66.29%					
130	-39.91%	-61.11%					
131	-46.34%	-48.15%					
132	-43.33%	-51.71%					
133	-46.83%	-57.10%	-18.01%	-21.55%	-23.21%	-49.28%	-56.65%
134	-48.30%	-38.86%					
135	-49.59%	-65.81%					
136	-45.03%	-70.98%					
137	-45.27%	-46.15%					
138	-52.48%	-57.10%					
139	-57.44%	-60.53%					
140	-45.15%	-52.99%	-8.87%	-22.38%	-16.01%	-43.31%	-50.59%
141	-46.10%	-39.94%					
142	-38.19%	-48.52%					
143	-46.19%	-56.25%					
144	-39.33%	-44.52%					
145	-44.35%	-62.25%					
146	-43.84%	-49.64%					
147		-67.40%	-6.54%	-28.49%	-14.72%	#DIV/0!	-49.93%
148		-36.74%					
149		-31.52%					
150		-60.53%					
151		-48.52%					
152		-47.67%					
153		-57.10%					
154	-47.57%	-63.03%	-4.69%	-12.98%	-23.15%	-47.34%	-56.37%
155	-53.35%	-45.95%					

	M	N	O	P	Q	R	S
156	-42.17%	-48.52%					
157	-45.03%	-68.26%					
158	-45.03%	-55.39%					
159	-51.53%	-49.38%					
160	-46.70%	-64.05%					
161	-39.86%	-51.85%	-1.43%	-8.76%	-17.18%	-43.35%	-38.40%
162	-44.88%	-56.95%					
163	-52.43%	-31.21%					
164	-43.17%	-14.08%					
165	-33.16%	-27.13%					
166	-42.89%	-48.52%					
167	-47.07%	-39.09%					
168	-48.31%	-42.81%	-3.91%	-14.33%	-20.14%	-49.42%	-57.59%
169	-51.76%	-57.20%					
170	-51.96%	-30.51%					
171	-49.81%	-59.62%					
172	-47.95%	-78.55%					
173	-46.35%	-58.88%					
174	-49.82%	-75.55%					
175	-47.44%	-43.17%	-11.64%	-17.60%	-22.04%	-49.48%	-59.59%
176	-53.39%	-58.06%					
177	-45.79%	-59.53%					
178	-49.26%	-78.95%					
179	-43.57%	-47.40%					
180	-51.82%	-57.81%					
181	-55.09%	-72.24%					
182		-57.65%	-7.30%	-20.20%	-19.52%	#DIV/0!	-55.61%
183		-67.72%					
184		-38.41%					
185		-55.43%					
186		-57.34%					

	M	N	O	P	Q	R	S
187		-50.74%					
188		-61.97%					
189	-53.82%	-65.43%	-7.93%	-23.86%	-24.64%	-47.86%	-65.41%
190	-44.84%	-72.81%					
191	-41.67%	-65.43%					
192	-49.57%	-47.57%					
193	-41.88%	-70.51%					
194	-49.16%	-58.52%					
195	-54.07%	-77.61%					

APPENDIX E
NONDESTRUCTIVE TEST METHODS VS. FIRE ENDURANCE

E.1 Introduction

In general, high strength concrete has higher fire endurance than low strength concrete. Traditionally, nondestructive test methods were used to evaluate the strength of concrete. In this appendix, the nondestructive test results are compared with the residual fire endurance to investigate whether they are significantly correlated. For practical purposes, if the residual fire endurance of burned concrete can be evaluated by using nondestructive test methods based on the well established laboratory reference, it would be an extremely valuable step for evaluating fire damage of building.

The seven-point average percentage loss of rebound number and pulse velocity between first and second measurements are the indexes for the residual properties of burned concrete. These quantities are used to establish the correlation between the nondestructive test results and the residual fire endurance. All Schmidt rebound hammer test data and ultrasonic pulse velocity test data are listed in Appendix D. Table E-1 shows the seven-point average percentage loss of rebound number of each test specimen between first and second

Table E-1: Test results of the seven-point average percentage loss (- %) of rebound number between first and second measurement measured on 23 concrete slabs

Pre-exposure Fire Severity	Re-curing Time Lapse			
	30 Days		75 Days	
	Natural Environment Re-curing	Conditioning Room Re-curing	Natural Environment Re-curing	Conditioning Room Re-curing
60 Minutes	15.17 11.93 9.34	-0.56 7.69 12.03	7.19 16.82 5.49	19.60 13.11 11.05
30 Minutes	11.64 7.30 7.93	*** 7.32 7.54	18.01 8.87 6.54	4.69 1.43 3.91

*** Missing Specimen

measurement. The overall mean of the seven-point percentage loss of rebound number of 23 concrete slabs between first and second measurement is 9.33% with a standard deviation 5.09%. Table E-2 shows the seven-point average percentage loss of pulse velocity of each specimen between first and second measurement. The overall mean of the seven-point percentage loss of pulse velocity between first and second measurement of 23 concrete slabs is 24.46% with a standard deviation 6.11%.

The residual fire endurance before adjustment for moisture was used to establish the relationship between the nondestructive test results and residual fire endurance. Table E-3 shows the percentage loss of fire endurance[1] of 23 concrete slabs. The overall mean of the percentage loss of fire endurance is 25.22% with a standard deviation 6.80%.

All analyses in this Appendix are the results based on data from sample specimens, regardless of treatments. As such, the results are assumed to represent the lump sum effect of the three main-factor treatments.

The estimated product-moment correlation results are listed in Table E-4. The product-moment correlation

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[1] The percentage loss of fire endurance can be calculated by the equation:

$$TR'_{LOSS} = \frac{(89.65 - TR')}{89.65} * 100$$

Where:

89.65 = the average fire endurance of the control group before adjustment (minutes),

TR' = residual fire endurance of each burned concrete specimen (minutes).

Table E-2: Test results of the seven-point average percentage loss (- %) of pulse velocity between first and second measurement measured on 23 concrete specimens

Pre-exposure Fire Severity	Re-curing Time Lapse			
	30 Days		75 Days	
	Natural Environment Re-curing	Conditioning Room Re-curing	Natural Environment Re-curing	Conditioning Room Re-curing
60 Minutes	31.76 30.23 30.18	31.68 32.71 35.52	29.53 30.42 19.40	21.04 26.43 26.78
30 Minutes	22.04 19.52 24.64	*** 18.30 18.04	23.21 16.01 14.72	23.15 17.18 20.14

*** Missing Data

Table E-3: The percentage loss (- %) of fire endurance of 23 burned concrete specimens before adjustment for moisture content

Pre-exposure Fire Severity	Re-curing Time Lapse			
	30 Days		75 Days	
	Natural Environment Re-curing	Conditioning Room Re-curing	Natural Environment Re-curing	Conditioning Room Re-curing
60 Minutes	13.24 13.85 7.27	15.56 21.55 15.97	14.19 18.44 7.66	31.18 13.84 16.25
30 Minutes	16.89 -10.12 13.12	*** 25.28 25.31	4.75 9.04 9.95	5.52 13.52 5.57

*** Missing Specimen

coefficient measures the strength of the linear relationship between two variables on a scale of -1 to +1, with zero indicating no linear relationship. The p value is used to test whether the coefficient is significantly different from zero. The following pairs of variable are not significantly correlated.

RB_{LOSS}[2] with TR_{LOSS}[3]: has 0.2709 correlation coefficient with p value 0.2111;

VL_{LOSS}[4] with TR_{LOSS}: has 0.0787 correlation coefficient with p value 0.7211.

For reference purposes, a simple linear regression was applied to establish the relationship between the results of nondestructive and destructive tests even though the correlation coefficients shown in Table E-4 between variables are not significantly different from zero.

E.2 Relationship Between Percentage Loss of Rebound Number and Fire Endurance

The percentage loss of fire endurance of a burned concrete slab corresponding to the seven-point average percentage loss of rebound number of a concrete slab between

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[2] The seven-point average percentage loss of rebound number of each specimen between first and second measurement.

[3] The percentage loss of fire endurance of each burned concrete slab.

[4] The seven-point average percentage loss of pulse velocity of each specimen between first and second measurement.

Table E-4: Estimated product-moment correlation of percentage loss of measurements of 3 different test methods conducted on 23 burned concrete slabs

	TR_{LOSS}	RB_{LOSS}	VL_{LOSS}
TR_{LOSS}*		0.2709[a] (23)[aa] 0.2111[aaa]	0.0787 (23) 0.7211
RB_{LOSS}**	0.2709 (23) 0.2111		0.2512 (23) 0.2476
VL_{LOSS}***	0.0787 (23) 0.7211	0.2512 (23) 0.2476	

* Percentage loss of fire endurance;

** Percentage loss of rebound number;

*** Percentage loss of pulse velocity;

a Correlation coefficient;

aa Sample size;

aaa Two-tailed P value.

first and second measurement can be described by a linear model:

$$TR_{LOSS} = 10.8722 + 0.362216 * RB_{LOSS}$$

Where

TR_{LOSS} = percentage loss of fire endurance of a burned concrete slab,

RB_{LOSS} = seven-point average percentage loss of rebound number of a concrete slab between first and second measurement.

Table E-5 shows the "Table of Estimates" and "Lack-of fit Test." In the table of estimates, the above regression model shows no significant relationship between TR_{LOSS} and RB_{LOSS}, since the p value of the slope is greater than 0.05. In the same Table E-5, the lack-of-fit test compares the variance of the deviations around the fitted model to an estimate of the error variance obtained from replicate values of RB_{LOSS}. Since the p value for lack-of-fit is greater than 0.05, there is no significant lack-of-fit. However, because the R-Square value in the "Table of Estimates" is only 0.07, leaving 0.93 unexplained variation, the selected model was regarded as not adequate to described the relationship between TR_{LOSS} and RB_{LOSS}. It was concluded that there is no significant linear relationship. Higher order polynomial regressions were tested to search for a better model to describe the relationship between TR_{LOSS} and RB_{LOSS}, but the results failed to improve the R-Square value.

Table E-5: Table of estimates and lack-of-fit test of regression linear model for TR_{LOSS} with RB_{LOSS} pair Table of Estimates

Source	Estimate	Standard Error	t Value	P Value
Intercept	10.8722	2.96958	3.66	0.0015*
Slope	0.362216	0.280822	1.29	0.2111
R-Square	Correlation Coeff.			
0.0734	0.271			

Lack-of-fit Test

Source	DF	Sum of Squares	F Value	P Value
Model	1	74.6829	1.66	0.2113
Error	21	942.69		
Lack-of-fit	20	827.827	1.54	0.2468
Pure Error	1	114.913		
Corrected Total	22	1017.37		

* Significant at α level at 0.05

E.3 Relationship Between Percentage Loss of Pulse Velocity and Fire Endurance

The percentage loss of fire endurance of a burned concrete slab corresponding to the seven-point average percentage loss of pulse velocity of a concrete slab between first and second measurement can be described by a linear model:

$$TR_{Loss} = 12.108 + 0.087655 * VL_{Loss}$$

Where

TR_{Loss} = percentage loss of fire endurance of a burned concrete slab,

VL_{Loss} = seven-point average percentage loss of pulse velocity of a concrete slab between first and second measurement.

Table E-6 shows the "Table of Estimates" and "Lack-of fit Test." In the table of estimates, the above regression model shows no significant relationship between TR_{Loss} and VL_{Loss}, since the p value of the slope is greater than 0.05. In the same Table E-6, the lack-of-fit test compares the variance of the deviations around the fitted model to an estimate of the error variance obtained from replicate values of VL_{Loss}. Since the p value for lack-of-fit is less than 0.05, the lack-of-fit is significant. This condition also is reflected in the R-Square value od 0.006. Therefore, it was concluded that the selected model is not adequate to described the relationship between TR_{Loss} and VL_{Loss}. There is no significant linear

Table E-6: Table of estimates and lack-of-fit test of regression linear model for TR_{LOSS} with VL_{LOSS} pair Table of Estimates

Source	Estimate	Standard Error	t Value	P Value
Intercept	12.108	6.10055	1.98	0.0604
Slope	0.0876546	0.242272	0.36	0.7211
R-Square	Correlation Coeff.			
0.0062	0.079			

Lack-of-fit Test

Source	DF	Sum of Squares	F Value	P Value
Model	1	6.3024	0.13	0.7138
Error	21	1011.07		
Lack-of-fit	20	1010.537	112280.97	0.0023*
Pure Error	1	0.00045		
Corrected Total	22	1017.37		

* Significant at α level at 0.05

relationship. Higher order polynomial regressions were tested to search the more appropriate model for describing the relationship between TR_{LOSS} and VL_{LOSS}, but the results failed to improve the R-Square value.

APPENDIX F
NONDESTRUCTIVE TEST METHODS USED TO EVALUATE COMPRESSIVE STRENGTH OF CONCRETE SPECIMEN

Because, physically, it is important to drill cores for conducting compressive tests after the first firing (60 minutes or 30 minutes pre-exposure severity treatment), there are no core test data available in this category. Therefore, in this research, the comparison of nondestructive and destructive test results for residual strength cannot be done. However, since the test results after second firing are all available, it is possible to compare strength of fire damaged concrete elements between results of the nondestructive and destructive methods to validate the use of nondestructive test methods.

F.1 Results of Drilled Core Compressive Strength Test

Two nondestructive tests and a drilled core compressive test were conducted on two untreated fresh concrete slabs, Tr_{999}-A and Tr_{999}-B, prior to the entire experimental process so as to establish a basis for calibration. These two slabs were made of the same batch of ready-mixed concrete as all test specimens. The slabs were cured for 28 days followed by moisture control in the drying room. Four test points were

Table F-1: Data summary of the nondestructive tests and compressive test on the two untreated fresh concrete slabs

No. of Specimen and Test Points		Measured Rebound Number	Measured Pulse Transit Time (μs)	Strength of Drilled Core (psi)	Measured Concrete Situation	
					Temp. (°F)	RH (%)
Tr_{999}-A	1	33.0	23.8	4166.63	73.4	53.3
	2	32.5	24.8	2938.96		
	3	33.0	24.6	5803.52		
	4	36.5	24.6	2782.95		
Tr_{999}-B	1	33.0	22.1	3495.4	76.2	49.7
	2	34	23.5	4269.16		
	3	38	23.3	3530.37		
	4	32	20.8	3421.82		
Mean		33.75	23.4375	3801.1		
Standard Deviation		2.435	1.3866	960.126		
Std. Skewness*		0.9845	-1.4346	1.823		
Std. Kurtosis**		0.20585	0.5344	1.4484		

* The standardized skewness tests whether variables deviate significantly from a normal distribution by looking at symmetry or lack thereof. For data which comes from a normal distribution, the standardized skewness will usually be between -2 and +2.

** The standardized kurtosis tests whether variables deviate significantly from a normal distribution by looking at the shape of the distribution relative to the normal curve. For data which comes from a normal distribution, the standardized kurtosis will usually be between -2 to + 2.

randomly selected in each slab, and the test results are listed in Table F-1.

Because of the limited sample size of this experimental design the core samples can be only taken from concrete specimen after the second firing. Therefore the final compressive strength of the concrete was measured from core test and represent the combined results of the effects of all treatments and the second firing. For comparison, it is assumed that the original compressive strength of the drilled cores taken from all concrete specimens have the same sample mean 3801.1 psi with a standard deviation of 960.126 psi. The percentage loss of compressive strength of drilled cores can be calculated by using the following equation.

$$SR\ \% = \frac{S_f - S_o}{S_o} * 100$$

where

$SR\ \%$ = percentage loss of core compressive strength of test point;

S_f = the core compressive strength of each test point after second firing;

S_o = the average core compressive strength of concrete slabs, Tr_{999}-A and Tr_{999}-B.

All core compressive test results are listed in Appendix D, which includes the compressive strength of drilled core, the percentage loss of compressive strength of each test

Table F-2: Test results of the seven-point average percentage loss (- %) of drilled core compressive strength measured on 23 concrete slabs

Pre-exposed Fire Severity	Re-curing Time Lapse			
	30 Days		75 Days	
	Natural Environment Re-curing	Conditioning Room Re-curing	Natural Environment Re-curing	Conditioning Room Re-curing
60 Minutes	51.30 43.36 48.41	53.91 53.42 63.13	55.10 46.32 46.41	45.39 59.57 63.13
30 Minutes	59.59 55.61 65.41	*** 47.25 49.56	56.65 50.59 49.93	56.37 38.40 57.59

*** Missing Specimen

points, and the seven-point average percentage loss of compressive strength of each test specimen. Brief results are listed in Table F-2. The overall mean of the seven-point average percentage loss of drilled core compressive strength of 23 burned concrete slabs is 52.89% with standard deviation 6.87%.

F.2 Correlations between Results of Nondestructive and Destructive Test Methods

One of the objectives of this study is to establish the relationships among different test results related to various damage situations. In this study the measurement used to evaluate the fire damage of concrete elements is percentage loss of different test readings (i.e., rebound number, ultrasonic pulse velocity, and the drilled core compressive strength) on the same test point in different phases. Using the difference in test results is to measure the fire damage while minimizing the external effects. Therefore, if a significant correlation between the results of nondestructive test and destructive test can be established, then the fire damage can be evaluated by using nondestructive test methods. For instance, after a fire the investigator can use nondestructive test equipment to test both undamaged structural elements and damaged structural elements; calculate the average percentage loss of the test reading; and use the established reference regression data to determine the extent of damage caused by fire.

In order to establish the correlation between the nondestructive and destructive test results, the data used to correlate to the drilled core compressive strength of concrete specimen of two nondestructive tests are the percentage loss of readings between first and third measurement. The percentage loss of rebound number between first and third measurement of each test point and the percentage loss of pulse velocity between first and third measurement are listed in Appendix D.

All data presented in this Appendix were the results of different test methods that are assumed to represent the lump sum effects of the three main-factor treatments and the second firing. These data can be used to evaluate the extent of fire damage, in terms of compressive strength, of concrete specimens under different environmental conditions by using Schmidt rebound hammer and ultrasonic pulse velocity tester. Therefore, the data from the three-way factorial design can be combined and all the factors independently affect the test results.

All the 161 test points were used to conduct the statistical test for a linear correlation between the percentage loss of rebound number and the percentage loss of drilled core compressive strength, and between the percentage loss of pulse velocity and the percentage loss of drilled core compressive strength. The statistical information is tabulated in Table F-3. The estimated product-moment

Table F-3: Statistics data of percentage loss of 3 test readings on 161 test points

	Percentage Loss of Rebound Number	Percentage Loss of Pulse Velocity	Percentage Loss of Drill Core Compressive Strength
Sample Size	161	140*	161
Mean	18.8924	45.4499	52.8863
Standard Deviation	10.2416	5.5461	14.2209
Std. Skewness**	-0.736034	-1.85991	-2.15327
Std. Kurtosis***	1.26996	0.773909	-0.35944

* 21 test points missing (3 slabs with too fragile exposed surface)

** The standardized skewness tests whether variables deviate significantly from a normal distribution by looking at symmetry or lack thereof. For data which comes from a normal distribution, the standardized skewness will usually be between -2 and +2.

*** The standardized kurtosis tests whether variables deviate significantly from a normal distribution by looking at the shape of the distribution relative to the normal curve. For data which comes from a normal distribution, the standardized kurtosis will usually be between -2 to + 2.

correlation test information is listed in Table F-4.

In Table F-4, the correlation coefficient measures the strength of the linear relationship between two variables on a scale of -1 to +1. The P value is used to test whether the coefficient is significantly different from zero. The following pairs of variables are significantly correlated at the $\alpha = 0.05$ level:

RB_{LOSS}[1] with ST_{LOSS}[2]: has 0.1569 correlation coefficient with P value 0.0468;

VL_{LOSS}[3] with ST_{LOSS}: has 0.2392 correlation coefficient with P value 0.0044.

According to these test results, both coefficients of correlation are positive and significantly greater than 0. These results indicate that a simple linear regression can be applied.

F.2.1 Relationship between Percentage Loss of Rebound Number and Drilled Core Compressive Strength

Based on the test data of 161 test points, the percentage loss of drilled core compressive strength corresponding to the percentage loss of rebound number can be described by a linear

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[1] The percentage loss of rebound number between first and third measurement at same test point.

[2] The percentage loss of core compressive strength of each test point.

[3] The percentage loss of pulse velocity between first and second measurement of each test point.

Table F-4: Estimated product-moment correlation of percentage loss of 3 test measurement on 161 test points

	RB_{LOSS}	VL_{LOSS}	ST_{LOSS}
RB_{LOSS} *		0.0019[a] (140)[aa] 0.9827[aaa]	0.1569 (161) 0.0468
VL_{LOSS} **	0.0019 (140) 0.9827		0.2392 (140) 0.0044
ST_{LOSS} ***	0.1569 (161) 0.0468	0.2392 (140) 0.0044	

* Percentage loss of rebound number;

** Percentage loss of pulse velocity;

*** Percentage loss of drilled core compressive strength;

a Correlation coefficient;

aa Sample size;

aaa Two-tailed P value.

model:

$$ST_{LOSS} = 48.7703 + 0.217867 * RB_{LOSS}$$

Where

ST_{LOSS} = Percentage loss of drilled core compressive strength;

RB_{LOSS} = Percentage loss of rebound number.

Table F-5 shows the "Table of Estimates" and "Lack-of-fit Test." In the table of estimates, the above regression model shows a significant relationship between ST_{LOSS} and RB_{LOSS} at the $\alpha = 0.05$ significant level, since the P value of the slope is less than 0.05.

Also, in same Table F-5, the lack-of-fit test compares the variance of the deviations around the fitted model to an estimate of the error variance obtained from replicate values of RB_{LOSS}. Since the P value for lack-of-fit is greater than 0.05, there is no significant lack-of-fit at the $\alpha = 0.05$ significance level. Therefore, the selected model is adequate to describe the relationship between ST_{LOSS} and RB_{LOSS}. However, this selected fitted curve should be used with caution even though the data in table of estimates and lack-of-fit test is satisfied. This caution is given because the R-Square[4] value is small.

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[4] R-Square is called the coefficient of determination, and it is often used to judge the adequacy of a regression model.

Table F-5: Table of estimates and lack-of-fit test of regression linear model for RB_{LOSS} with ST_{LOSS} pair

Table of Estimates

Source	Estimate	Standard Error	t Value	P Value
Intercept	48.7703	2.33547	20.88	0.0000*
Slope	0.217867	0.108755	2.00	0.0468*
R-Square	Correlation Coeff.			
0.0246	0.157			

Lack-of-fit Test

Source	DF	Sum of Squares	F Value	P Value
Model	1	769.596	4.01	0.0468*
Error	159	31560.7		
Lack-of-fit	150	30377.1	1.54	0.2468
Pure Error	9	1183.67		
Corrected Total	160	32357.3		

* Significant at α level at 0.05

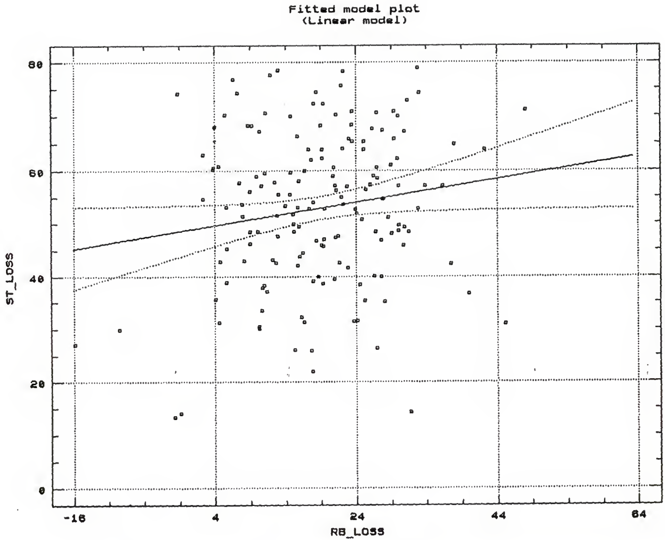

Figure F-1: Fitted curve with 95% confidence limits of the regression linear model for RB_{Loss} and ST_{Loss} pair

On the other hand, based upon the empirical assessment of relationship using a scatter diagram of the two variables, shown in Figure F-1, there is no apparent linear relationship. In fact, the variation in the dependent variable appears to be unrelated to the independent variable. Regardless of the fact that there was a sufficiently large sample size to indicate a significant linear relationship, the lack of evidence of this linearity in Figure F-1 resulted in the discussion to abandon the rebound number as a predictor of residual compressive strength.

F.2.2 Relationship between Percentage Loss of Pulse Velocity and Drilled Core Compressive Strength

Based on the data of 140 test points, the percentage loss of drilled core compressive strength corresponding to the percentage loss of pulse velocity can be described by a linear model:

$$ST_{LOSS} = 24.6135 + 0.629456 * VL_{LOSS}$$

Where

ST_{LOSS} = Percentage loss of Drilled core compressive strength;

VL_{LOSS} = Percentage loss of pulse velocity.

Table F-6 shows the "Table of Estimates" and "Lack-of-fit Test." In the table of estimates, the above regression model shows a statistically significant relationship between ST_{LOSS}

Table F-6: Table of estimates and lack-of-fit test for regression linear model of VL_{LOSS} with ST_{LOSS} pair Table of Estimates

Source	Estimate	Standard Error	t Value	P Value
Intercept	24.6135	9.995826	2.47	0.0147*
Slope	0.629456	0.217502	2.89	0.0044*
R-Square	Correlation Coeff.			
0.0572	0.239			

Lack-of-fit Test

Source	DF	Sum of Squares	F Value	P Value
Model	1	1694.04	8.38	0.0044*
Error	138	27912.5		
Lack-of-fit	133	27627.5	3.64	0.0736
Pure Error	6	285.091		
Corrected Total	139	29606.6		

* Significant at α level at 0.05

and VL_{LOSS} at the 0.05 level of significance, since the P value of the slope is less than 0.05.

Also, in Table F-6, the lack-of-fit test compares the variance of the deviations around the fitted model to an estimate of the pure error variance obtained from replicate values of VL_{LOSS}. Since the P value for lack-of-fit is greater than 0.05, the linear model can not be rejected at the α = 0.05 significance level. Therefore, the selected model may be adequate to describe the relationship between ST_{LOSS} and VL_{LOSS}.

The scatter diagram of the two variables (see Figure F-2) indicates apparently that the strength of linear relationship may be significant in a statistical sense but includes substantial unexplained variation in a practical sense. The source of this variation may be uncontrolled characteristics of the specimens, the test procedures, or the measurement techniques or instruments. Further investigations are needed.

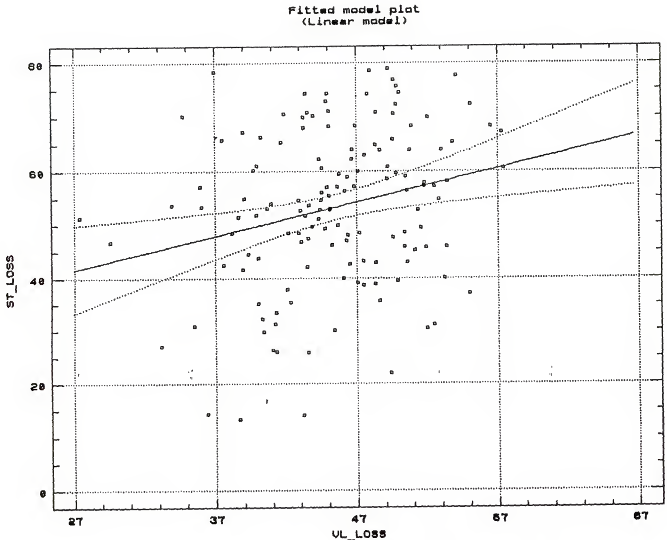

Figure F-2: Fitted curve with 95% confidence limits of the regression linear model for VL_LOSS and ST_LOSS pair

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BIOGRAPHICAL SKETCH

Kuang-hua Hsiung was born on October 29, 1956, in Yunlin, Taiwan, R.O.C. He graduated from Hsinchu Senior High School, in Hsinchu, Taiwan in June 1975. In June 1979 he received his Bachelor of Science from the Central Police College, in Taoyuan, Taiwan.

Kuang-hua served as captain in the Department of Fire and Rescue in Taipei from 1979 to 1982, after which he served as deputy fire chief in the Department of Fire and Rescue in Miaoli from 1982 to 1985. From 1982 to 1984, he entered the Graduate School of Police Science in the Central Police College, receiving a Master of Science in Fire Science and Administration in June 1984.

In August 1984 Kuang-hua jointed the faculty of the Central Police College teaching at the Department of Fire Science and Administration. In 1988 he received a the scholarship from the National Science Council of the R.O.C. to pursue his Ph.D. degree in the School of Building Construction at the University of Florida.

Kuang-hua was married to Kuang-jen Huang on December 4, 1984, in Taipei, Taiwan. They have two daughters, Yun-wen and Yun-jia, and one son, Ta-chung.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Weilin P. Chang, Chairman
Professor of Building Construction

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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